Detector and Physics Calibrations

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Acknowledgements

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- Notably: Guennadi Borissov, Adi Bornheim, Oliver Buchmueller, Georgios Daskalakis, Yuri Fisyak, Tapio Lampen, Marjorie Shapiro, Jan Stark, Mayda Velasco

Calibration and Alignment

- **Goal is to get the maximum out of your detector.**
  - Design performance or test beam performance is not guaranteed
  - Many more channels, often mass produced, conditions not controlled.

- **Calibration: what did you measure?**
  - ADC to energy, time to distance
- **Alignment: or "dude, where is my detector"?**

- **Each has a hardware component**
  - Lasers, light flashers, survey marks, pulsers, radioactive sources
- **And a software component**
  - Calibrate and align with data

Calibration and Alignment Caveat

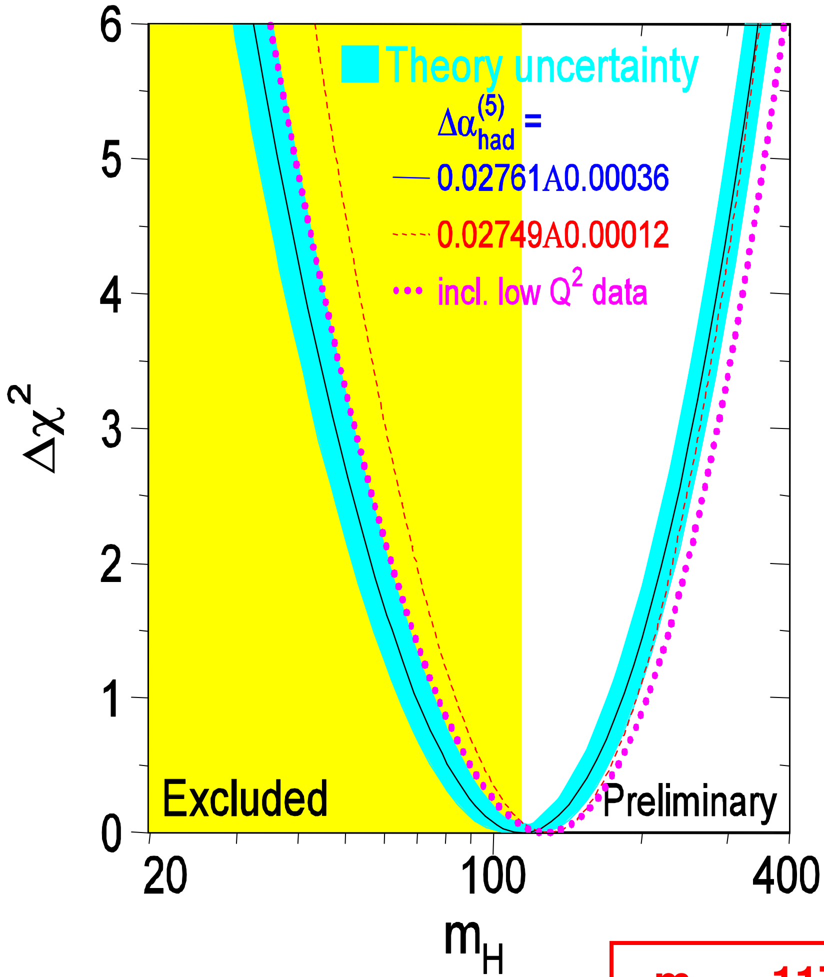
- **Generally considered to be an extremely boring topic.**
  - Success = only 50% of the audience is sleeping at the end of the talk

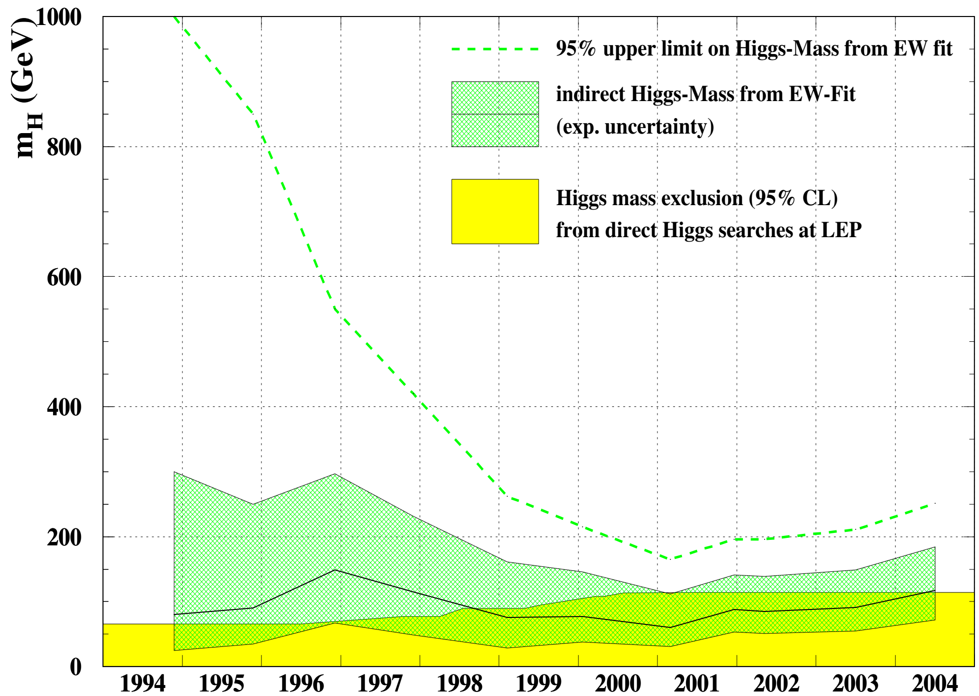
Calibration and Alignment – motivation

- **General Aesthetics**
  - With much time and effort, built beautiful detector, won't achieve maximum performance without calibration
- **Practical Considerations**
  - Discover Higgs
    - Need superb photon resolution
  - Discover supersymmetry
    - Understand missing Et resolution, most importantly the tails
  - Discover high mass states
    - Best momentum resolution possible
    - Alignment improves tracking efficiency
  - Third Generation may be key
    - Need excellent displaced vertex identification

LHC Question #1 - Low Mass Higgs ?

Is electroweak symmetry broken via the Higgs mechanism ?





$m_H = 117^{+67}_{-45}$ GeV (based on 2004 m_T = 178 GeV)

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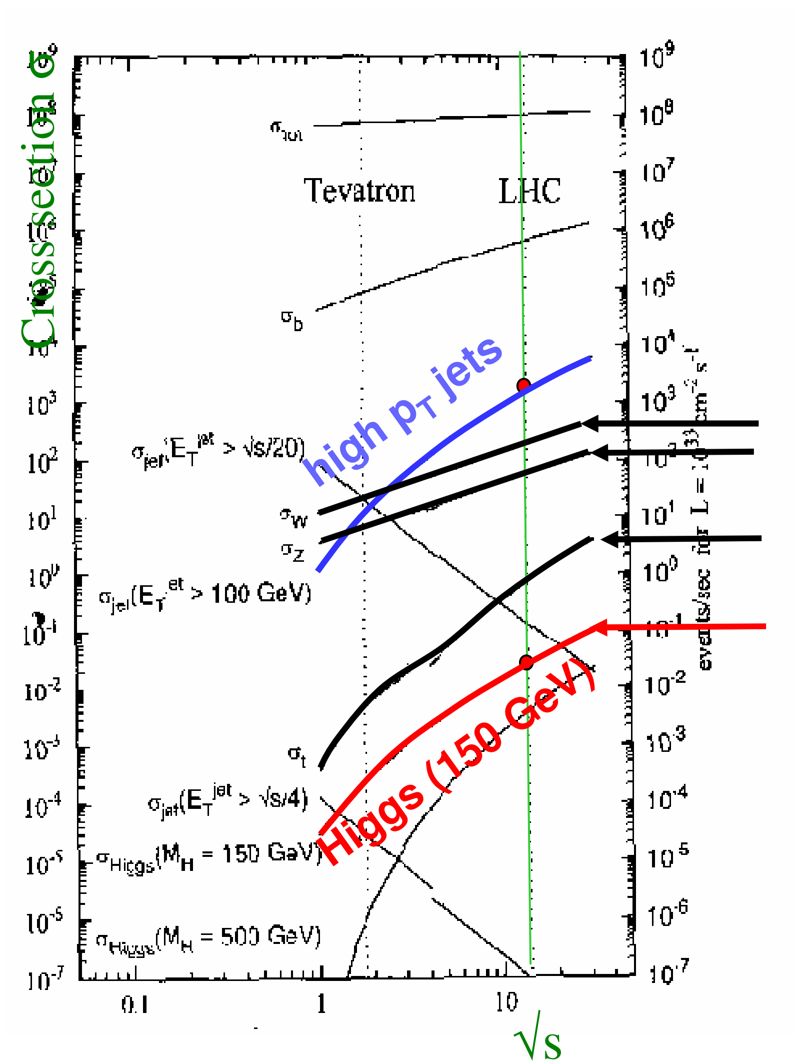
How good an ECAL do we need for H->γγ?



If the Higgs is light ….

$W^{+/-}$ m = 80.4 GeV Γ = 2.1GeV
Z^0 m = 91.2 GeV Γ = 2.5GeV **@ SPS : √s = 0.5 TeV**

t m = 178 GeV Γ ~ 1.5GeV @ Tevatron : √s = 2 TeV

H m = 150 GeV ? Γ = ~10 MeV @ LHC : √s = 14 TeV

Searching for a 10^{-10} branching ratio ! And ..

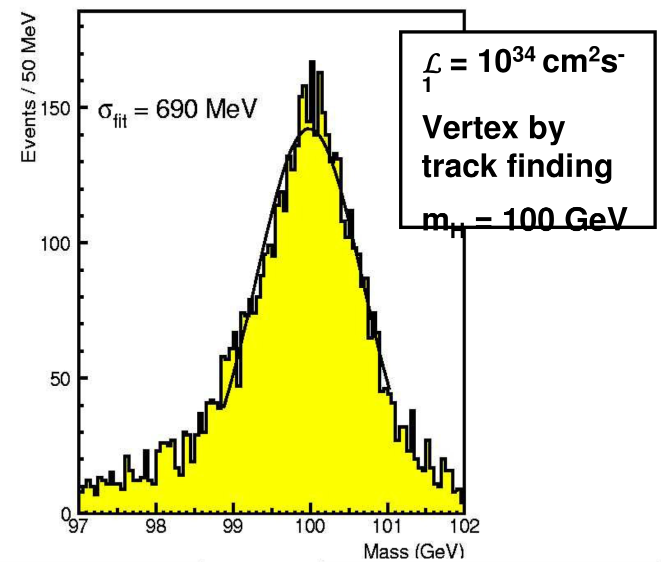
Resolution Required for Low Mass Higgs

Benchmark process: H $\rightarrow \gamma\gamma$

$$\boxed{m_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}\left(1-\cos\theta_{\gamma 1,\gamma 2}\right)}}$$

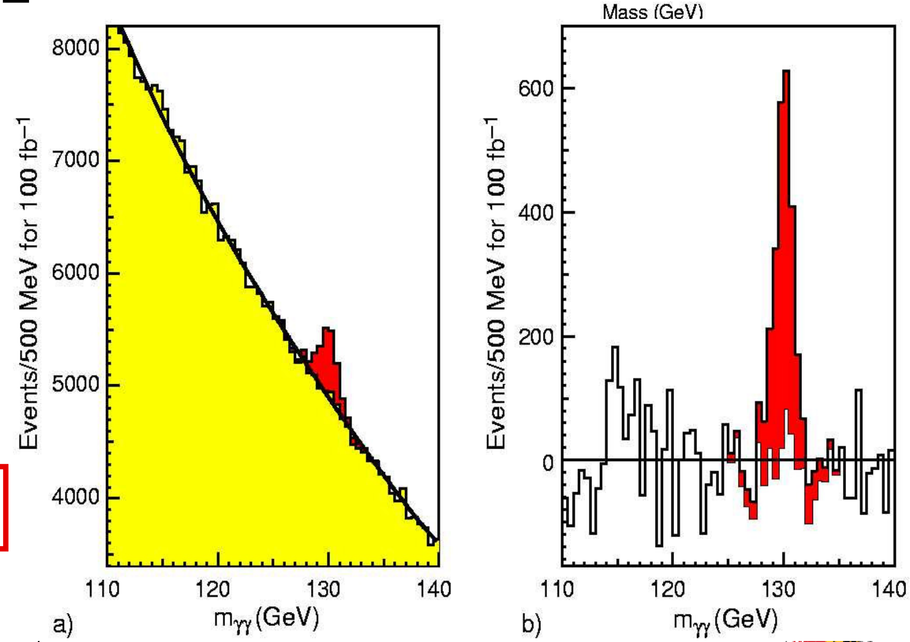
$$\boxed{\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{\tan(\theta_{\gamma\gamma}/2)}\right]}$$

($\delta\theta$ limited by interaction vertex measurement)



CMS Resolution : σ_E / **E = a** / √ **E** ⊕ **b** ⊕ **c/ E**

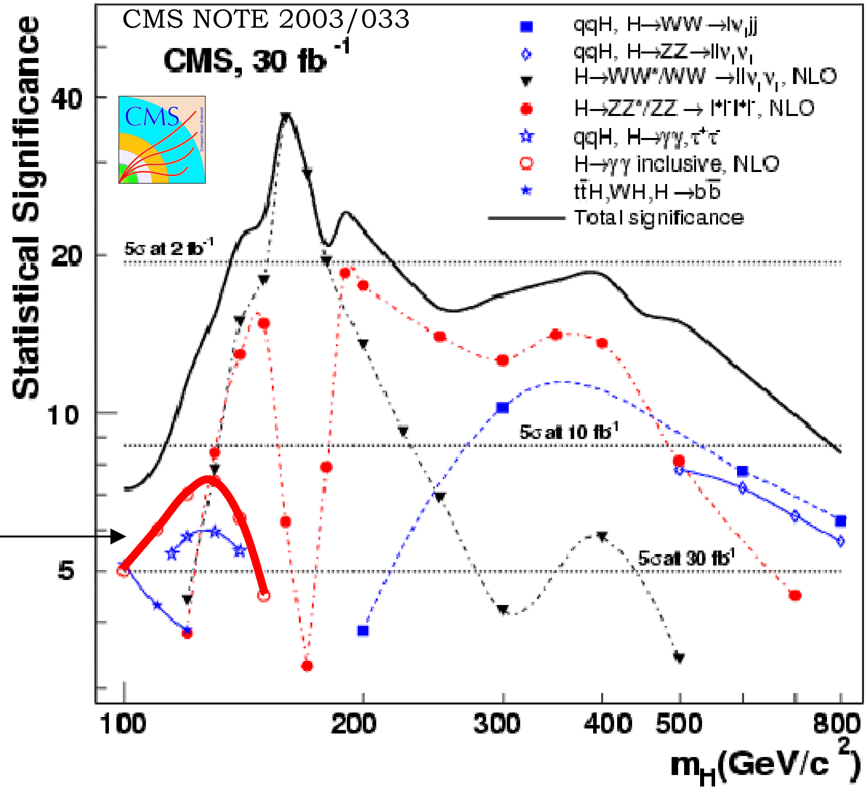
Aim:		Barrel	End cap
Stochastic term:	a =	2.7%	5.7%
Constant term:	b =	0.55%	0.55%
Noise: Low ℒ	c =	155 MeV	770 MeV
High ℒ		210 MeV	915 MeV



At 100 GeV : 0.27 ⊕ 0.55 ⊕ 0.002 ≅ 0.6%

Higgs Discovery Potential

H->γγ



Excellent ECAL performance and calibration is essential.

The constant term dominates and calibration will determine the constant term

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Supersymmetry

- **Important Discovery Channels**
  - Jets + missing Et or trileptons + missing Et
- **Cautionary note**
  - "Those who cannot remember the past are condemned to repeat it." George Santayana

π^0 -> e^+e^- Discovery (??) 1977
(π^0 -> $\gamma\gamma$ discovered 1950)

- π^0 -> e^+e^- "discovered" with BR 4 times modern value of 6.2×10^{-8}
- 5 events seen, 1 background claimed. With modern BR, only 1 event signal expected.
- Plot shows e+e- mass (x)
- Resolution tails hard

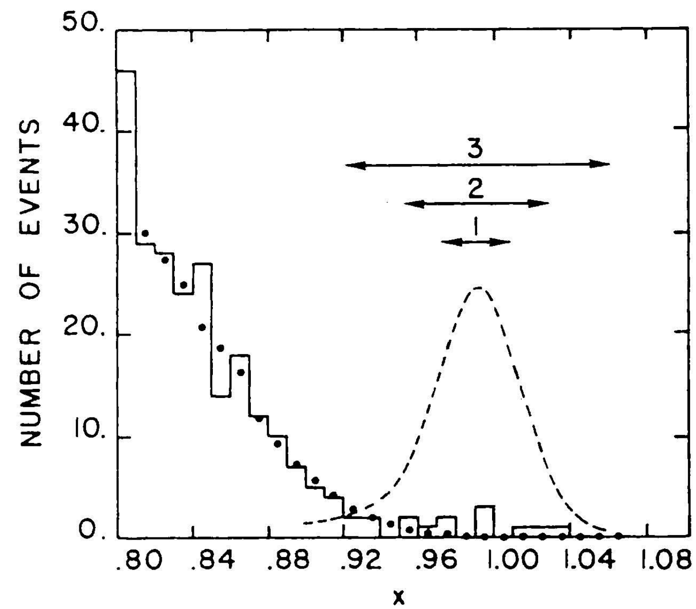
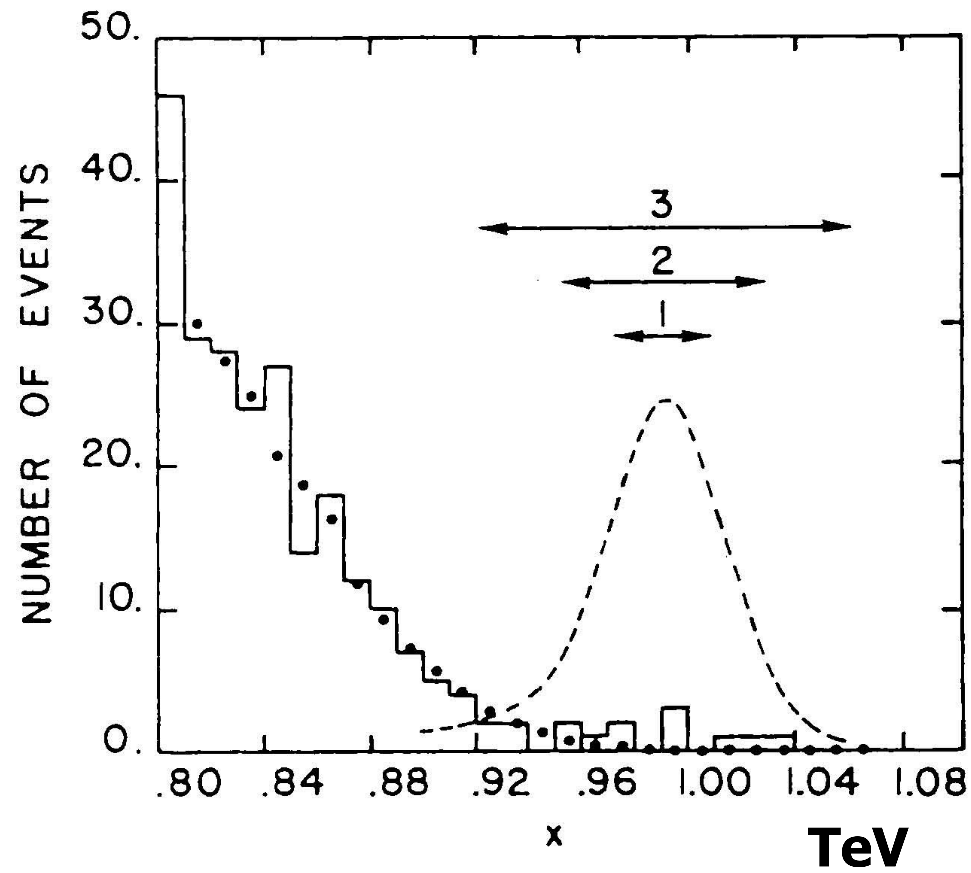


Fig. 1. e^+e^- effective-mass distribution before kinematic fit. Histogram: experimental sample, dots: Monte Carlo simulation. The expected distribution of $\pi^0 \to e^+e^-$ decays (dashed line) is plotted with an arbitrary scale factor. The double arrows represent the 3 bins of table 1.

Supersymmetry or ED Discovery (20XX)

- **Supersymmetry**
  - x = missing Et
- **Extra Dimensions**
  - x = μ+μ- mass
- **Essential to understand mean, sigma and non-gaussian tails**



Calorimeter Calibration

- **Will cover calibration first, then alignment.**
- **Will focus on CMS and Dzero, but stay general.**
  - One crystal and scintillator calorimeter, one LAR.
- **For ATLAS, see ATLAS Physics TDR**
  - http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html
- **For CMS, see CMS Physics TDR volume**
  - http://cmsdoc.cern.ch/cms/cpt/tdr/

ECAL Calibration and Alignment

- **Goal: approximately 0.5% constant term**

$$E = G \times F \times \sum C_i A_i$$

- **G = overall gain**
- **F = correction function depending on type of particle, position, energy and cluster algorithm used**
- **C_i = intercalibration constant**
- **A_i = signal amplitude (ADC) in channel i**

ECAL Calibration and Alignment

- **Calorimeter Alignment: use tracker, typically much better position resolution than calorimeter**

- **Calibration problem often factorizes.**
  - Overall scale vs stability
  - Electronics vs detector (crystals or LAR)
    - One changes often, one fixed (more or less)
  - Initial calibration vs calibration in situ

- **Details are detector specific**

ECAL Calibration and Alignment

- **During construction, often possible to calibrate with radioactive sources (e.g. ^{60}Co), pulsers and so on.**
  - Design mechanical tolerances for resolution goal.

- **Test beams used to get overall gain factor.**
  - Test beam conditions (material in front of calorimeter often different, electronics used may not be final, cables almost certainly not final.
  - Understand response as function of position

- **Cosmic ray muons can be useful.**

CMS ECAL Calibration & Monitoring

➢ECAL Calibration (Resolution : 'Constant Term of the Resolution Formula') :

Raw (uncalibrated) Supermodule : 6%-10% 'Resolution'
Spread among channels before calibration

→

Beam Test Precalibration : 2 % 'Resolution'
With a 'fast' calibration
'Lab Precalibration' : 4 % 'Resolution'

→

In-Situ Physics Calibration : 0.5 % 'Resolution'
Timescale for calibration : Weeks

➢ECAL Monitoring (Monitor Stability and Measure Radiation Effects) :

ECAL Stability (<< 0.5%) ,
Monitored with Laser Monitoring System

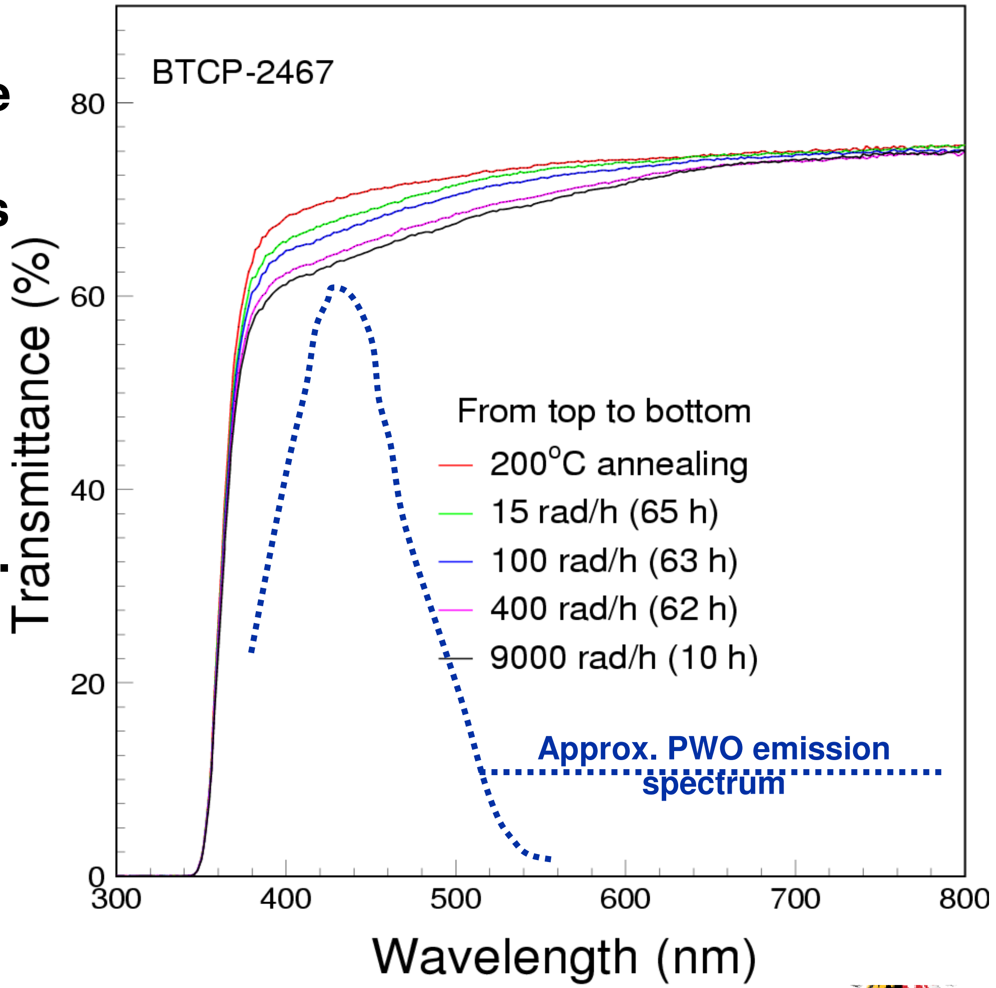
→

Transparency Loss Correction, Signal Change under Irradiation ~5%
Measured with Laser Monitoring System

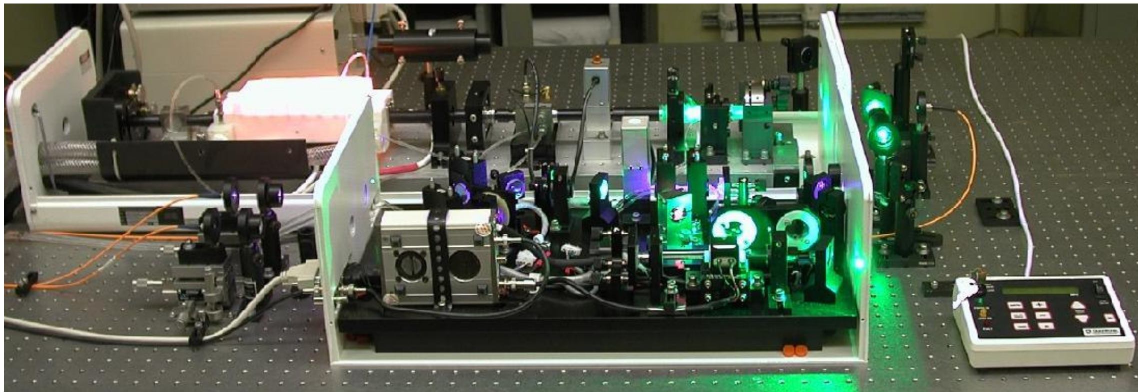
CMS: Radiation Effects PWO Transparency

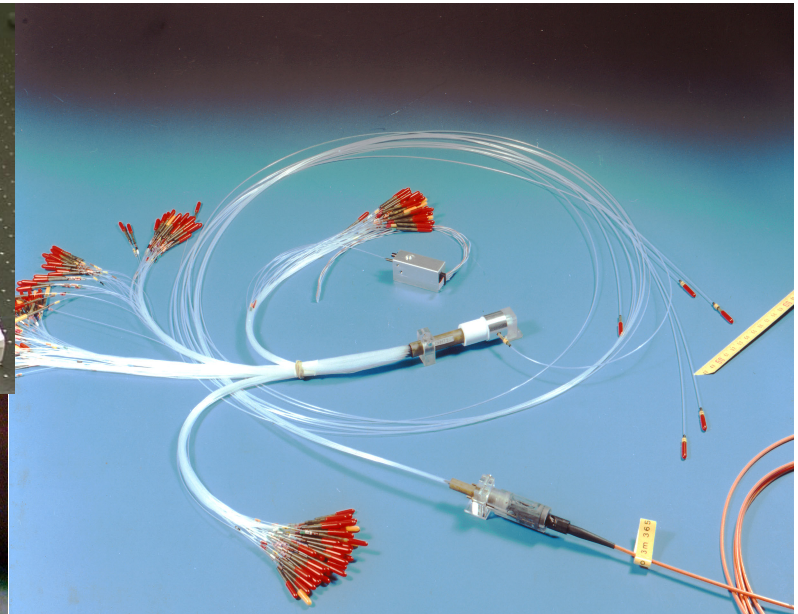
- Radiation reduces transparency in the **blue,** where PWO emission spectrum peaks
- Effect is **dose rate dependent**.
- Monitoring **relative change** of PWO transparency with pulsed laser light.

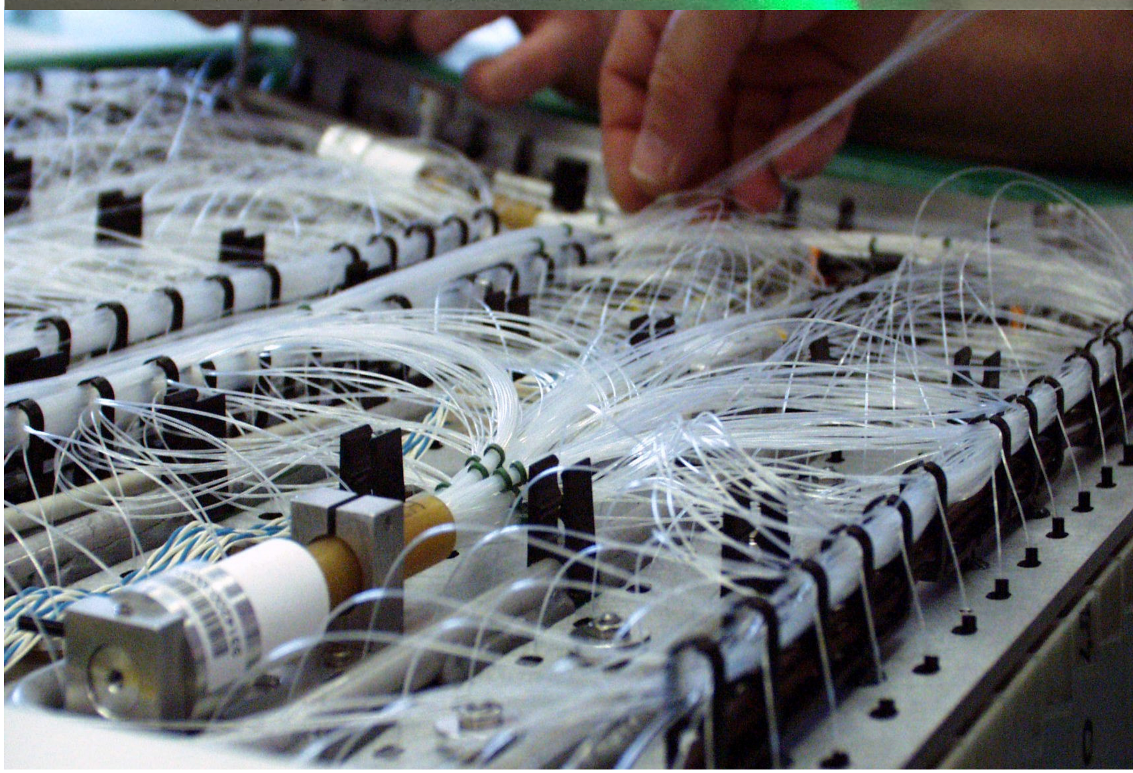
For CMS barrel (15 rad/hour) :
Transparency change at a level of ~5%.

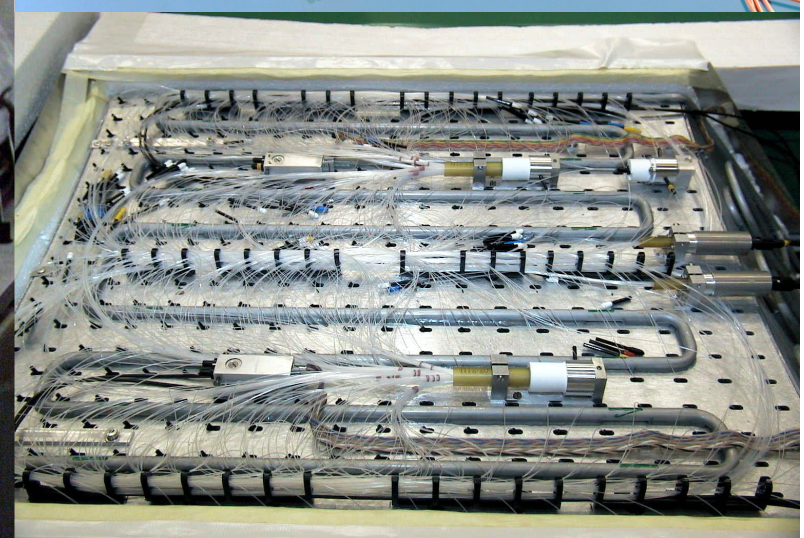


ECAL Laser Monitoring System



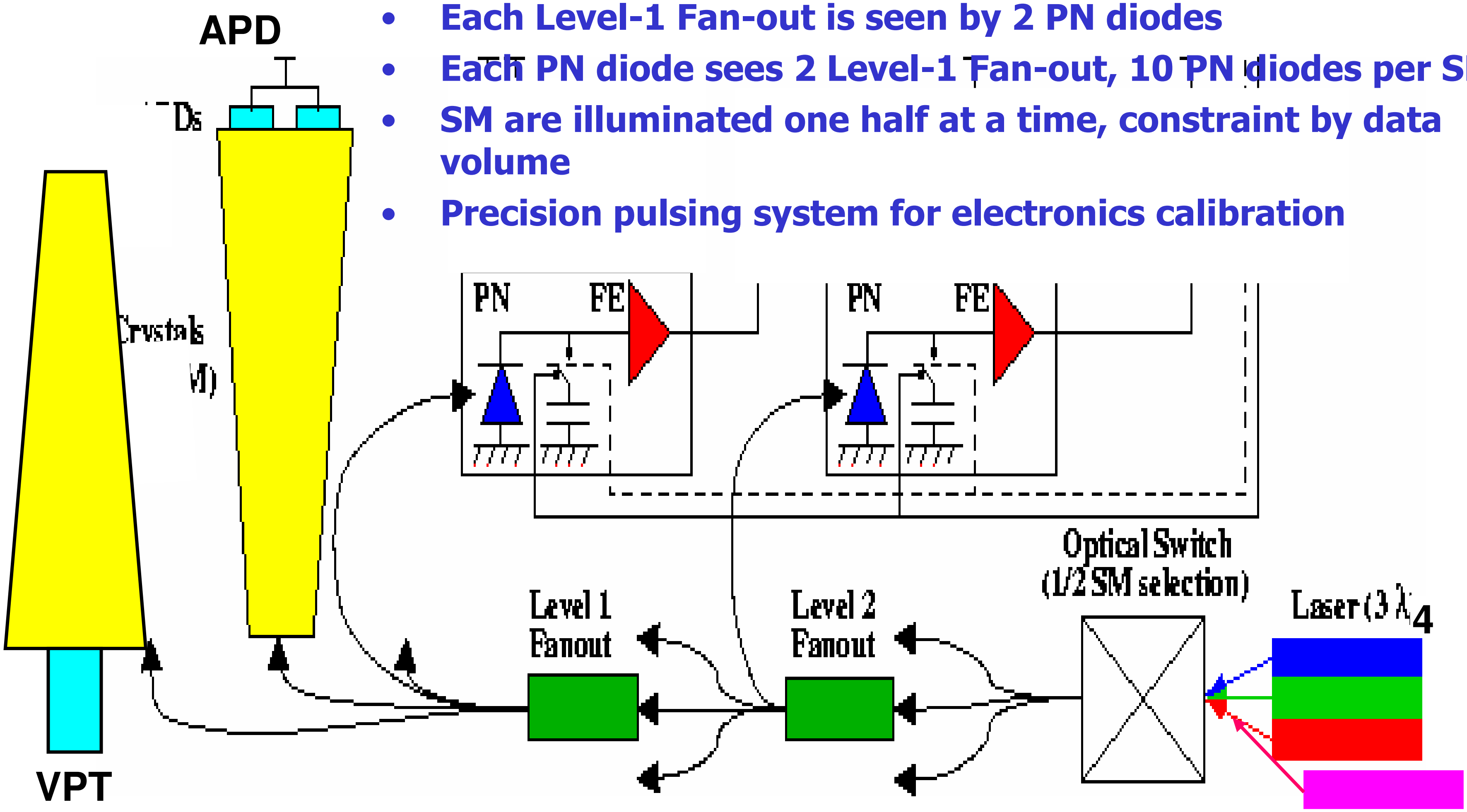






ECAL Laser Monitoring System

- Very stable PN-diodes used as reference system
- Each Level-1 Fan-out is seen by 2 PN diodes
- Each PN diode sees 2 Level-1 Fan-out, 10 PN diodes per SM
- SM are illuminated one half at a time, constraint by data volume
- Precision pulsing system for electronics calibration

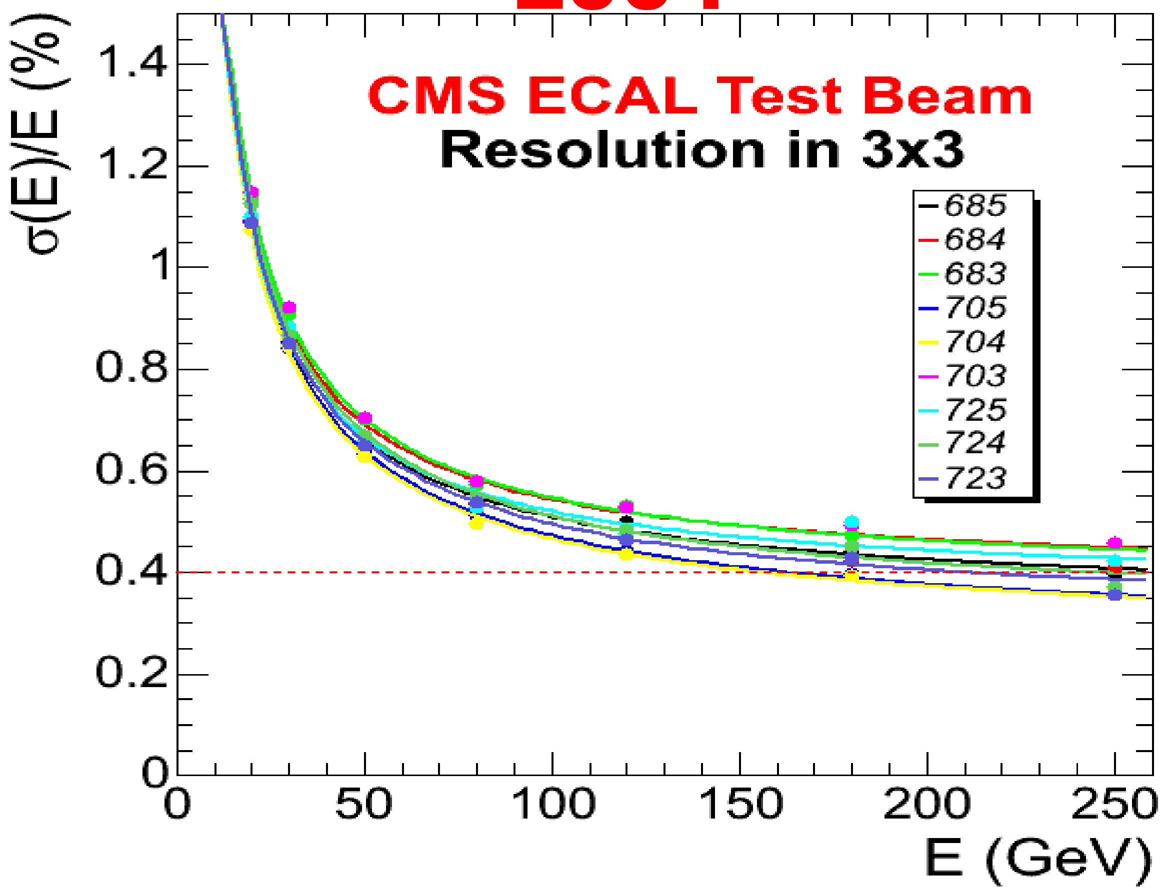


⇒Transparency of each crystal is measured with a precision of <0.1% every 20 minutes

Testbeam Measurements at CERN

- Electrons, pions, muons
- Precisely known energies
- Supermodules on moveable table
- Study of energy resolution, irradiation effects etc.

CMS ECAL Resolution in Test Beam 2004

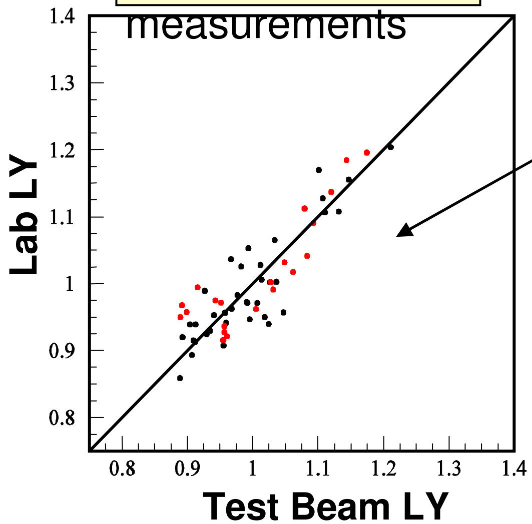


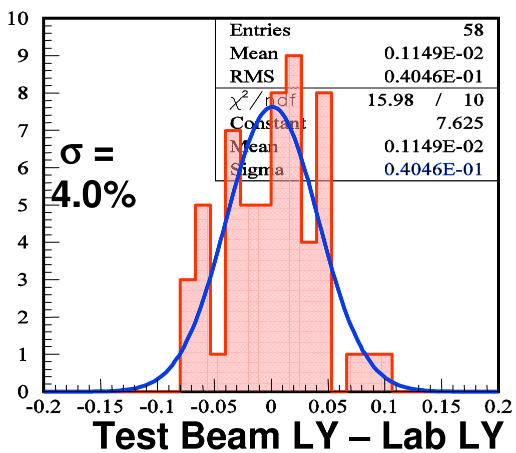
⇒ Design performance achieved in the test beam !

(Design resolution as well as noise, stability, …)

Calibration Strategies

Lab measurements → Pre-calibration → In-situ





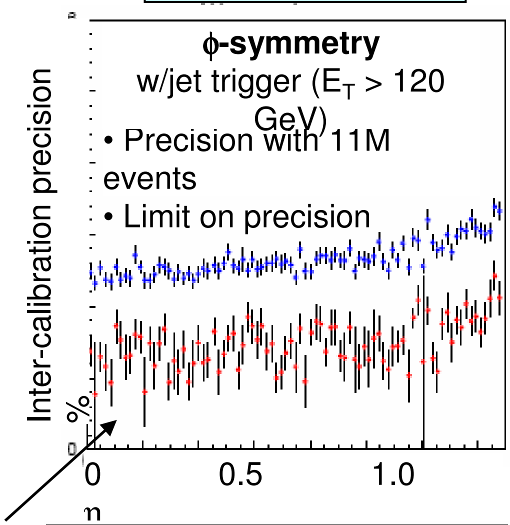
Initial pre-calibration by 'dead reckoning' based on lab measurements (~4%)

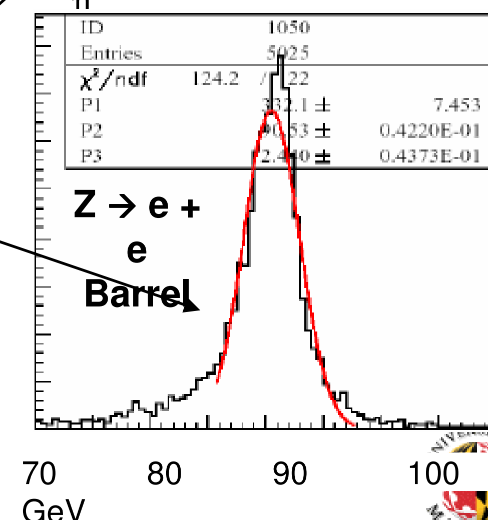
Reference pre-calibration of few SM with 50/120 GeV electrons in test beam (<2%)

Fast in-situ calibration based on principle that mean energy deposited by jet triggers is independent of ϕ at fixed η (after correction for Tracker material) (~2-3% in few hours)

ϕ-ring inter-calibration and $Z \rightarrow e + e$ cross-calibration (~1% in 1 day)

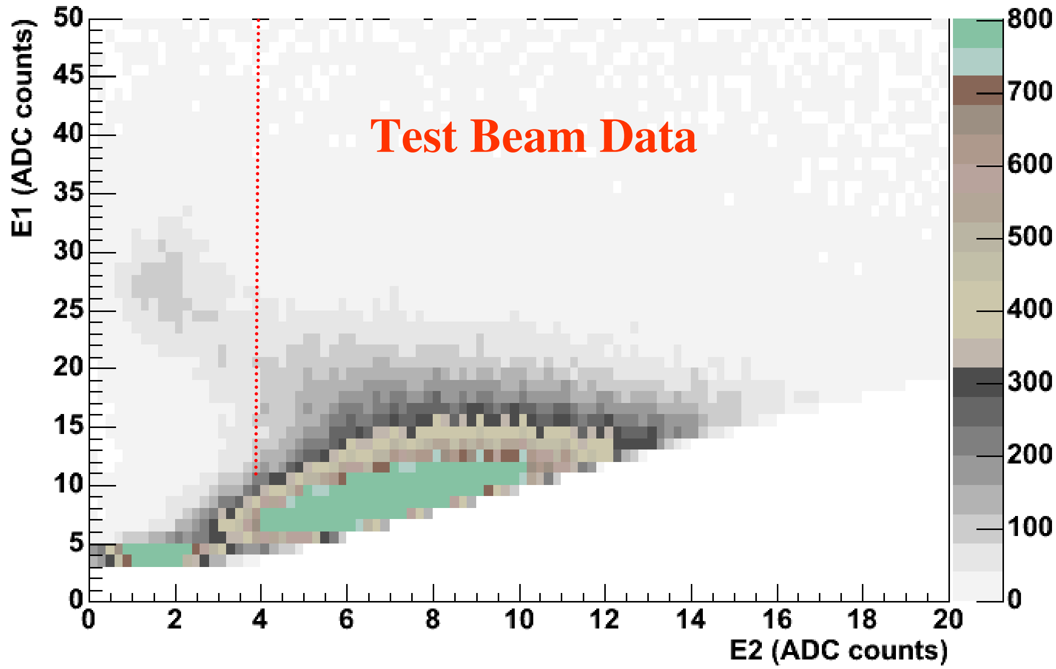
Finally: calibration to < 0.5% with W → νe in few months

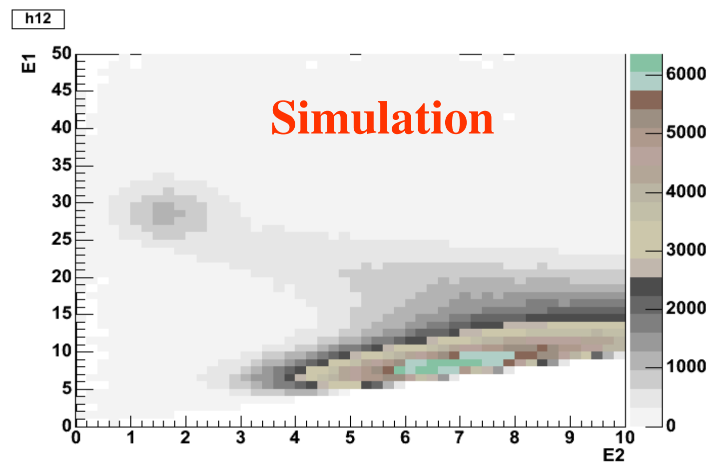




Cosmic Muon Calibration

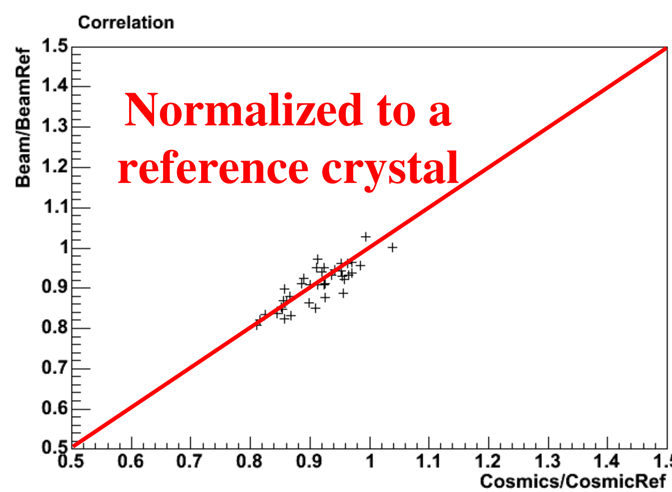
For APD gain (50) cosmic muons are hidden in the noise.
Run at higher gain (200).





E1 is the highest energy deposit (maximum sample)

E2 is the second highest energy deposit in the 3x3 matrix (evaluated at the same sample as E1)



Relative calibration ~ 2% achievable.

CMS ECAL in-situ Calibration Strategies

➢Very high precision :

0.5 % constant term

(Note : this accounts for inter-calibration, stability and transparency loss correction)

➢Hadron Collider at high luminosity :

No "standard candle" or golden events (e.g. Bhabhas), CM energy not fixed, Pile-up, very high cross-sections, and trigger issues for calibration events

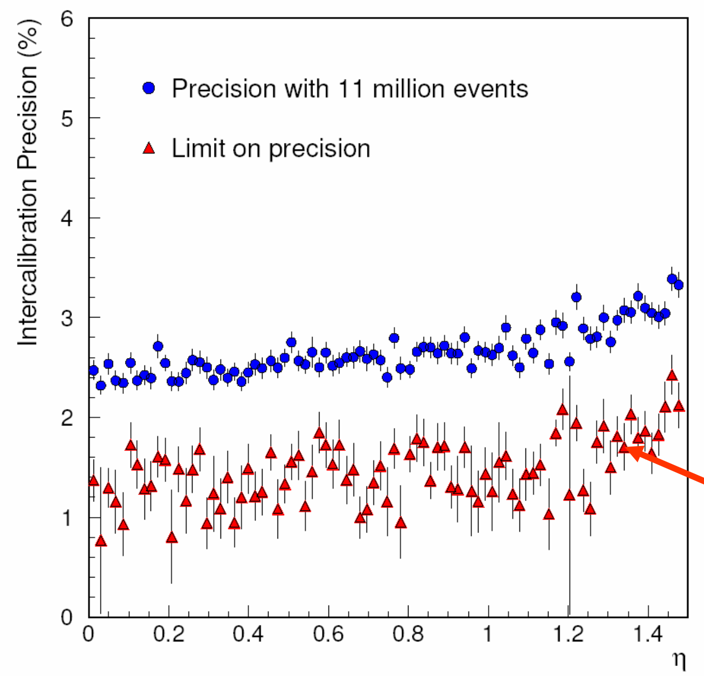
➢Perform calibration in a timely manner :

Key physics processes are only (or at least much much easier) accessible at low luminosity (pile up).

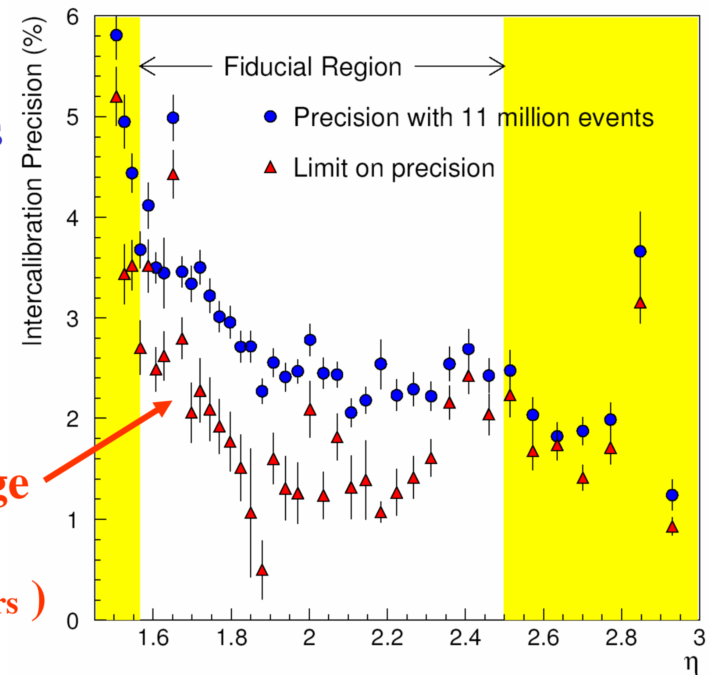
The performance of the ECAL will degrade over 10 years of LHC running (noise).

CMS In-situ : φ-uniformity method

BARREL



ENDCAPS



11 million
Level-1 jet trigger events

Precision limits assuming no knowledge of tracker material

(~10h , 1kHz L-1 single jet triggers)

Idea: φ-uniformity of deposited energy in crystals at constant η

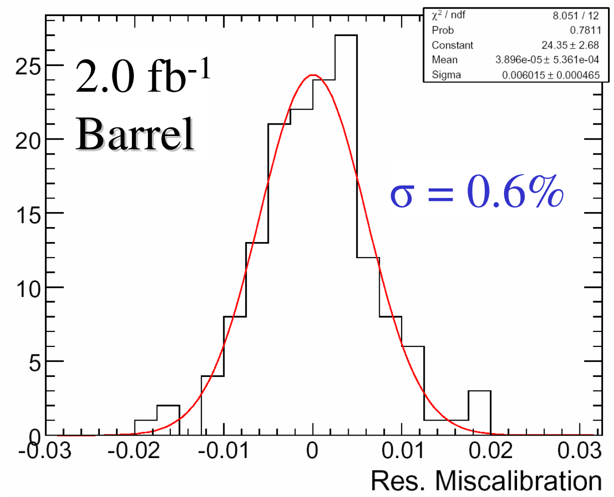
Used: Min-bias / Level-1 jet trigger events

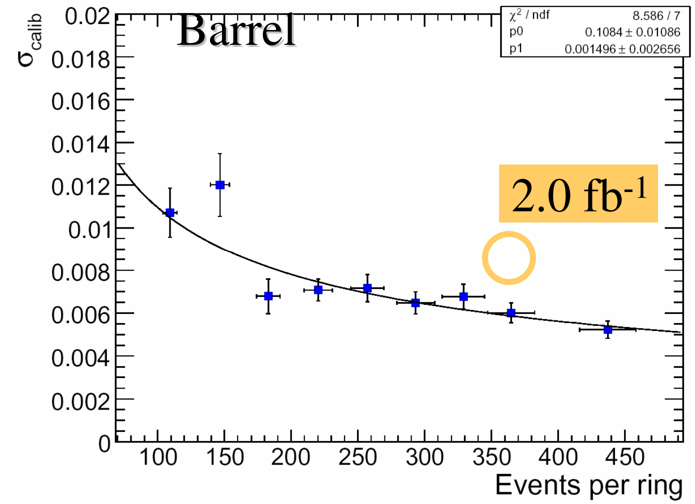
Method: Compare $<E_T>_{CRYSTAL}$ with $<E_T>_{RING}$.

Limitations : non-uniformities in φ
- in-homogeneity of tracker material
- geometrical asymmetries

Inter-calibration of η rings:
$Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-\gamma$, isolated electrons

CMS In-situ: using $Z\rightarrow e^+e^-$





Method:
Z mass constraint

Use cases:
- Inter-calibrate crystals in ECAL regions
- Inter-calibrate ECAL regions (i.e.rings in φ-symmetry method)
- Set the absolute energy scale
- Tune algorithmic corrections for electron reconstruction

Events Selection: Low brem electrons.

Algorithm:
Iterative (~10-15), constants are obtained from the peak of ε^i distribution.

$$\bar{\epsilon}^i = \frac{1}{2}\cdot\left[\left(\frac{M^i_{inv}}{M_Z}\right)^2 - 1\right]$$

Results:
Assuming 5% mis-calibration between the rings and 2% mis-calibration between the crystals within a ring

*Statistics: **2.0 fb^{-1}***

0.6% ring inter-calibration precision

CMS In-situ: using isolated electrons

Target: 0.5% calibration precession

Sources: $W \to e\nu$ (10Hz HLT @ $2\times10^{33}cm^{-2}s^{-1}$),
$Z \to e^+e^-$ (2Hz HLT @ $2\times10^{33}cm^{-2}s^{-1}$),
$J/\Psi \to e^+e^-$, $b/c \to e$, …

Method: E / P <width minimization>

ECAL

$$E = \sum^{5x5} c_i E_i$$

TRACKER
electron
momentum

Event Selection:
We need a narrow E/P $\Rightarrow$ Low brem $e^{\pm}$
Variables related to electron bremsstrahlung :
ECAL (S_{3x3}/S_{5x5})
TRACKER (track valid hits, χ^2/n.d.f., P_{out}/P_{in})
Efficiency after HLT: 20-40% Barrel ,
10-30% Endcaps

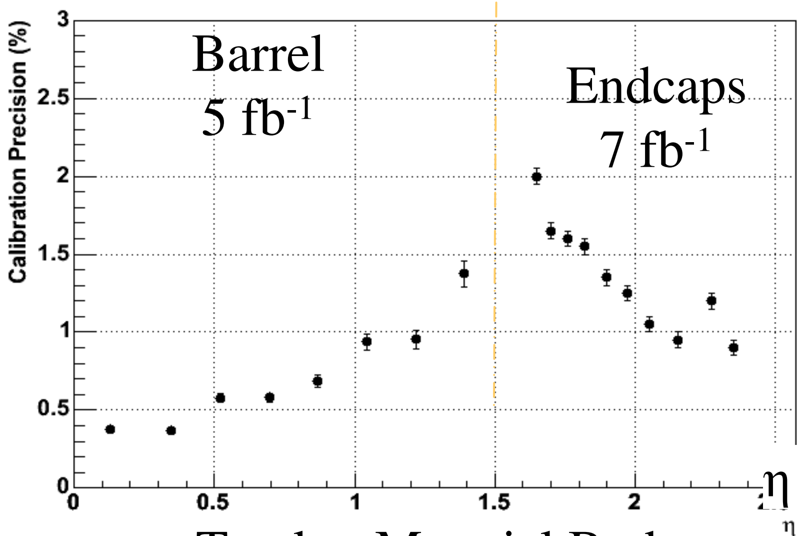
Background: S/B~8
(isol. electrons from W/QCD)
Part of it might be useful ($b/c \to e$).

Calibration Constants extraction Techniques:
- L3/LEP iterative (~20 iterations),
- matrix inversion

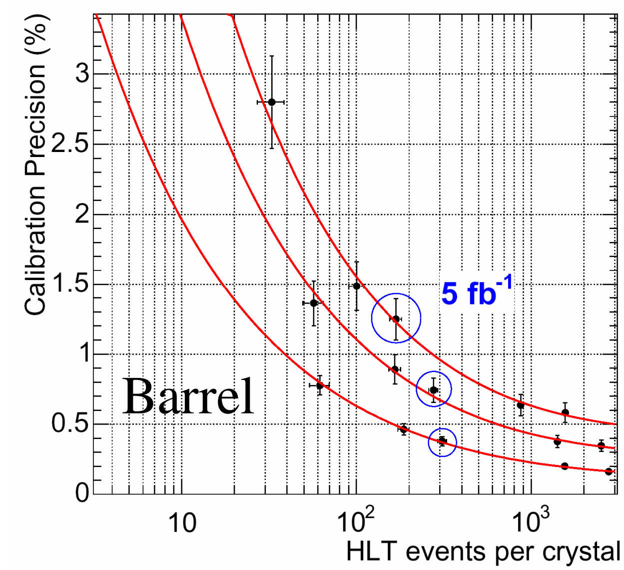
Calibration Steps
- Calibrate crystals in small η-φ regions
- Calibrate regions between themselves using tighter electron selection, $Z \to e^+e^-$, $Z \to \mu^+\mu^-\gamma$

In-situ: using isolated electrons

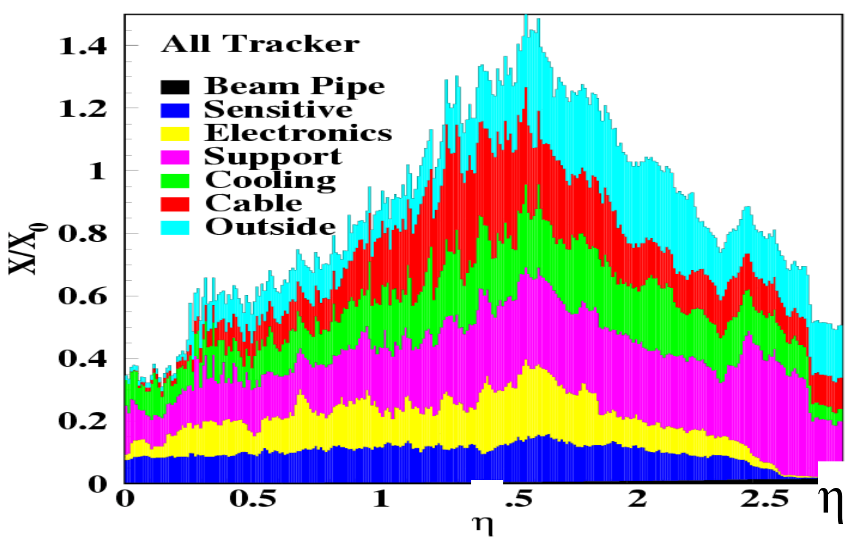
Calibration Precision versus η



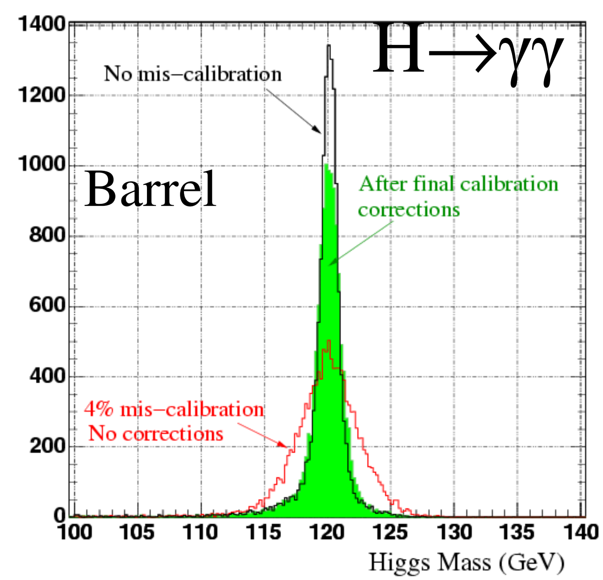
Precision versus Statistics



Tracker Material Budget



Higgs Boson Mass Resolution



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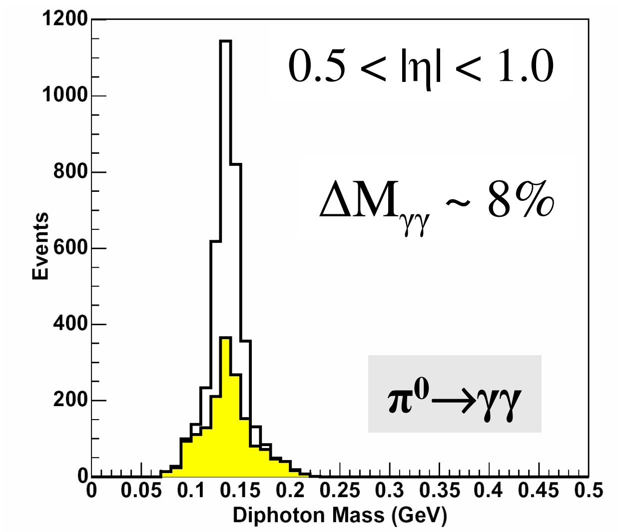
In-situ: $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$



Method:
Mass constraint for crystal inter-calibration.

Unconverted photons are in-sensitive of the tracker material

Selection : shower shape cuts per γ, small γ opening angles (60-90mm)

$\pi^0 \to \gamma\gamma$:

"Common" π^0s; can be found in L1 e/m triggers (source: jets or pileup events)

Efficiency ~ **1.4%**
Level-1 rate : **25kHz**
} ~**2days** $\Rightarrow$ **1K** ev./crystal ⇨ ~ **0.5%** stat. inter-calibr. precision

$\eta \to \gamma\gamma$:

Much lower rate after background suppression
Better mass resolution ~ 3%

… they seem promising … still under study …

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ECAL Calibration: Reality Check

- **In Monte Carlo, calibration is always easier. Events are clean, weird effects absent.**
- **The detector won’t be exactly phi symmetric.**
- **It won’t be built exactly as drawn.**
- **The trigger will be biased.**

- **Full understanding of signal process, from ionization/light production thru the electronics to final storage will likely be necessary.**
  - Examples from Dzero.

Electromagnetic showers

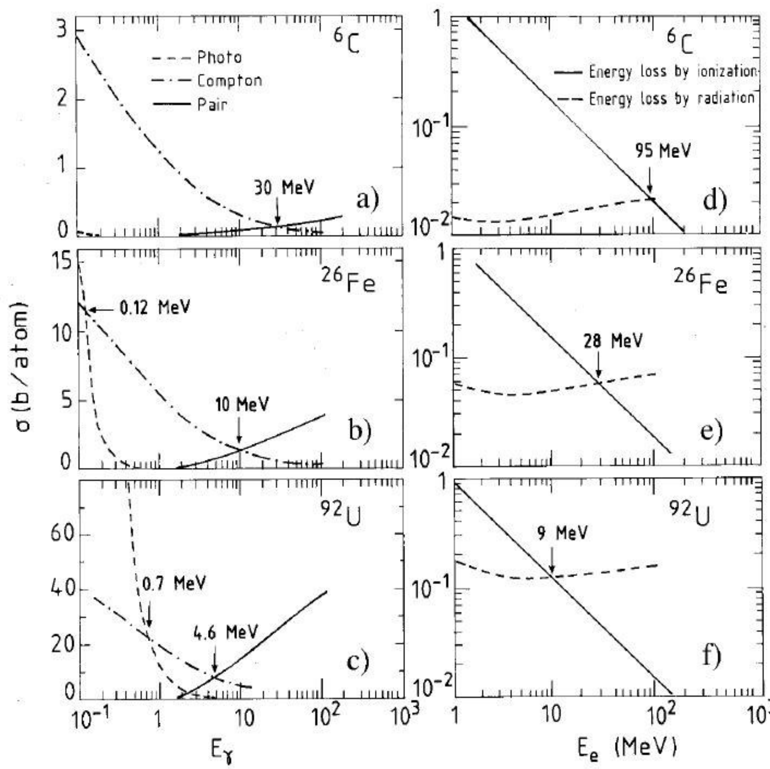


FIG. 2.1. Cross sections for the processes through which the particles composing electromagnetic showers lose their energy, in various absorber materials. To the left are shown the cross sections for pair production, Compton scattering and photoelectric effect in carbon (*a*), iron (*b*) and uranium (*c*). To the right, the fractional energy losses by radiation and ionization are given as a function of the electron energy in carbon (*d*), iron (*e*) and uranium (*f*).

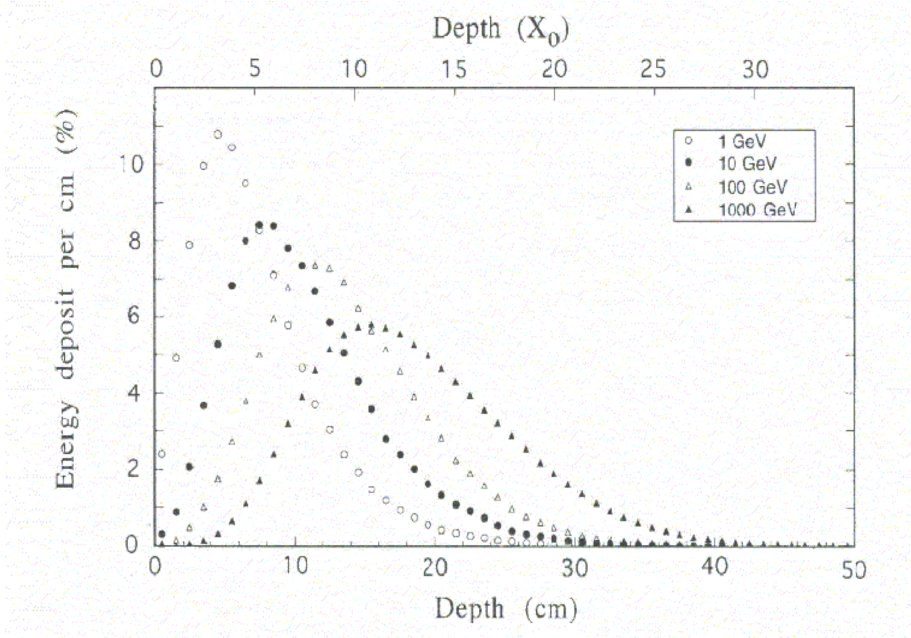
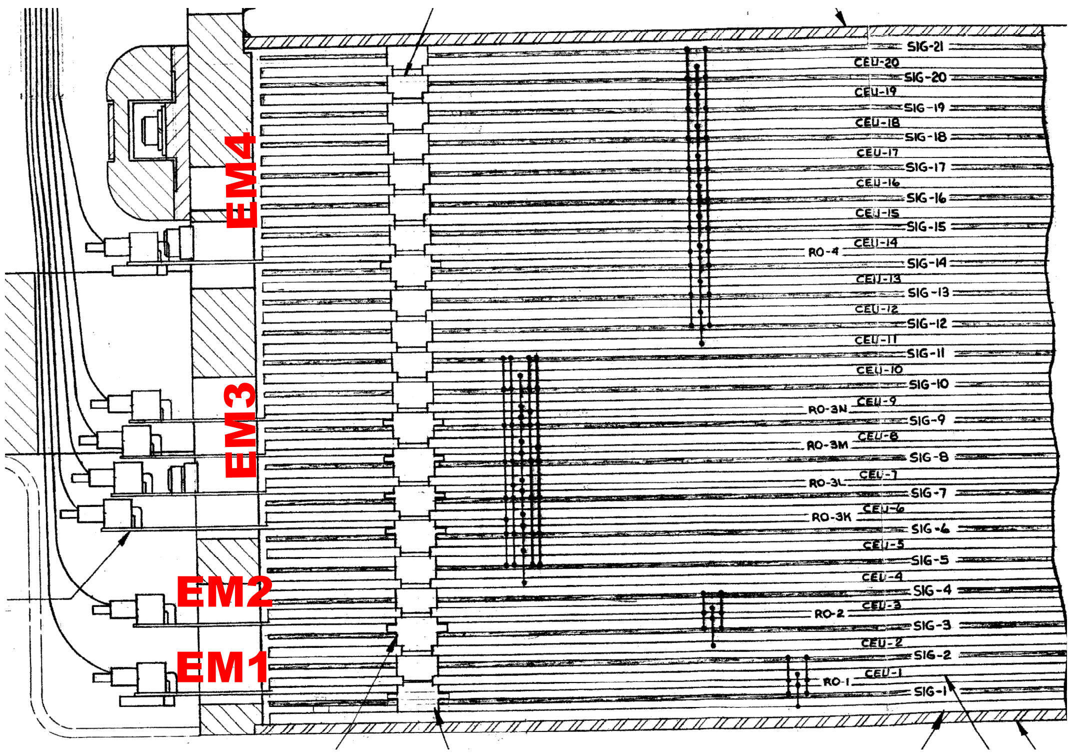


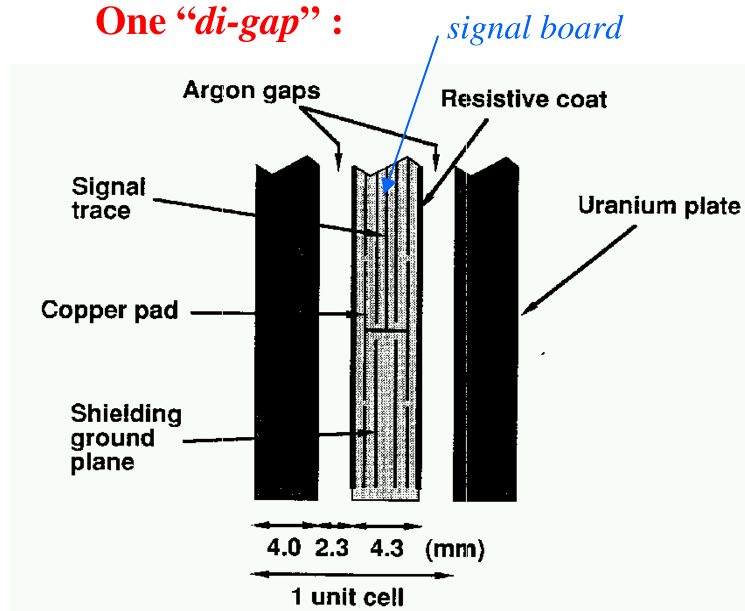
Figure 4: The energy deposit as a function of depth, for 1, 10, 100 and 1000 GeV electron showers developing in a block of copper. In order to compare the energy deposit profiles, the integrals of these curves have been normalised to the same value. The vertical scale gives the energy deposit per cm of copper, as a percentage of the energy of the showering particle. Results of EGS4 [8] calculations. This figure has been taken from Ref. [9].

DØ is a “U/LAr sampling calorimeter”

More detailled view of one CC-EM module :



One “*di-gap*” :



incident particle

sampling fraction: 15 %

Basically a stack of Uranium plates with liquid Argon in between. Shower develops in U and LAr (mainly U); charged shower particles ionise the Argon atoms => current in Argon because of HV applied across each gap. This current is measurable
(thanks to electronic charge amplifiers with very large gain).
EM1, EM2, EM3 and EM4 are read out separately; each one of these layers regroups a number of digaps.

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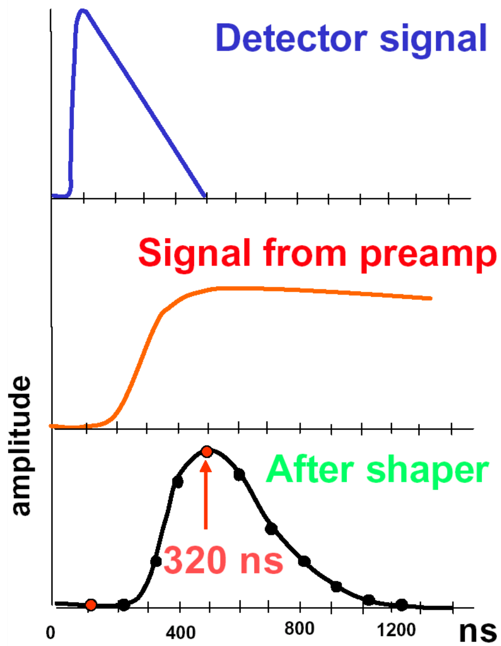
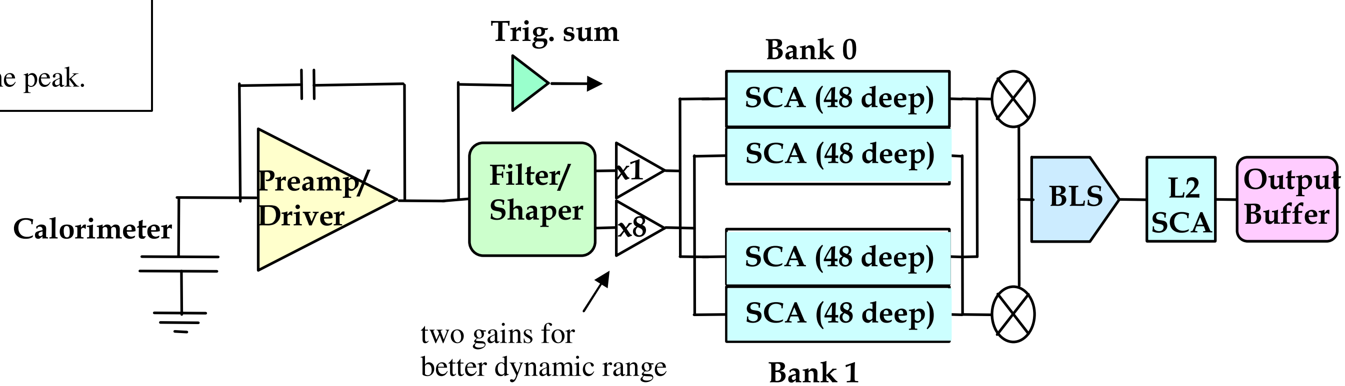
DØ Basics of the readout

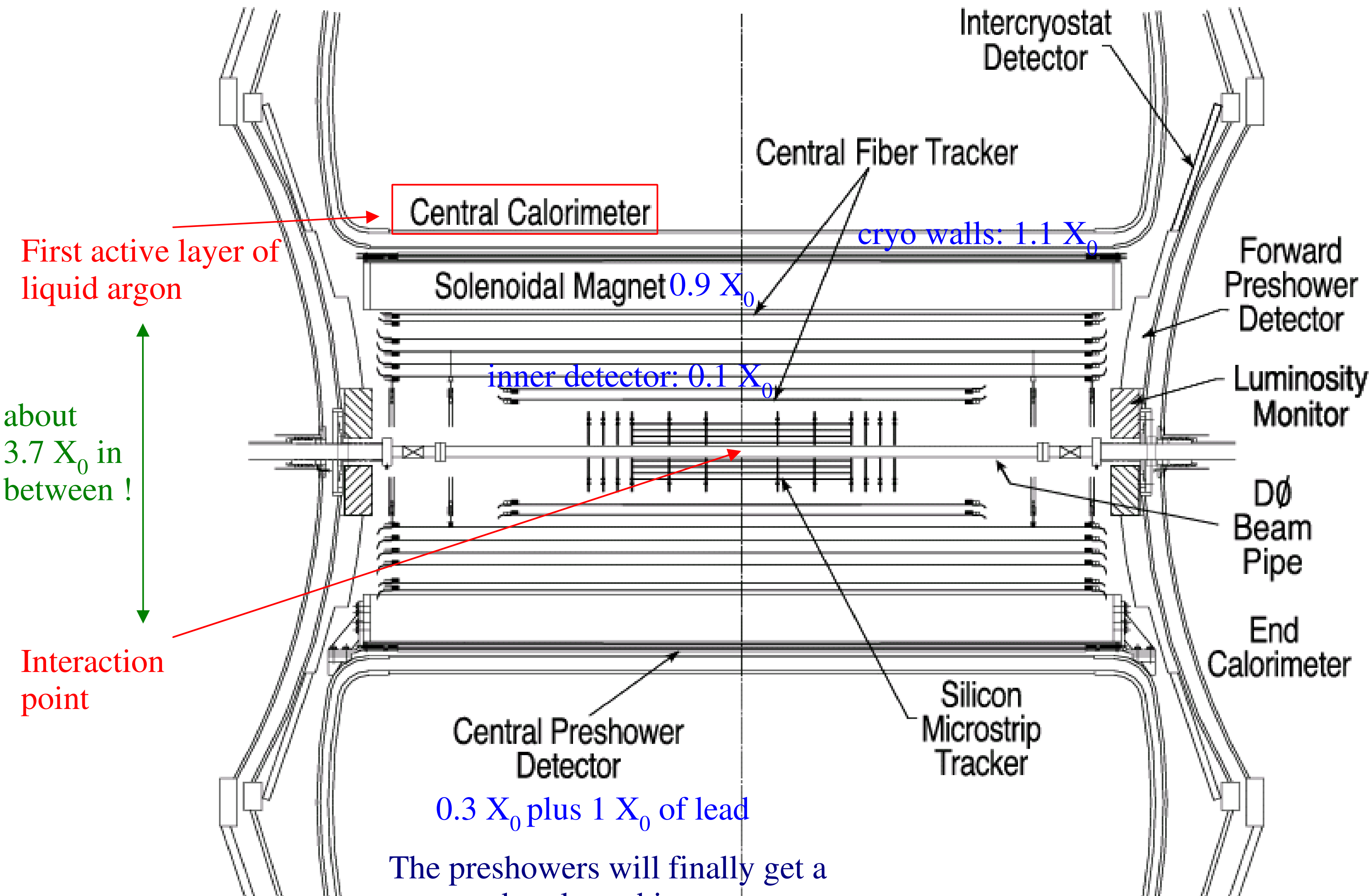


Have ability to sample and
record the shaped signal
also at (320 ± 120) ns
to make sure we are on the peak.

- Detector signal ~ 450 ns long
  (bunch crossing time: 396 ns)
- Charge preamplifiers
- BLS (baseline subtraction) boards
  - short shaping of ~2/3 of integrated signal
  - signal sampled and stored every 132 ns in analog buffers (SCA) waiting for L1 trigger
  - samples retrieved on L1 accept, then baseline subtraction to remove pile-up and low frequency noise
  - signal retrieved after L2 accept
- Digitisation



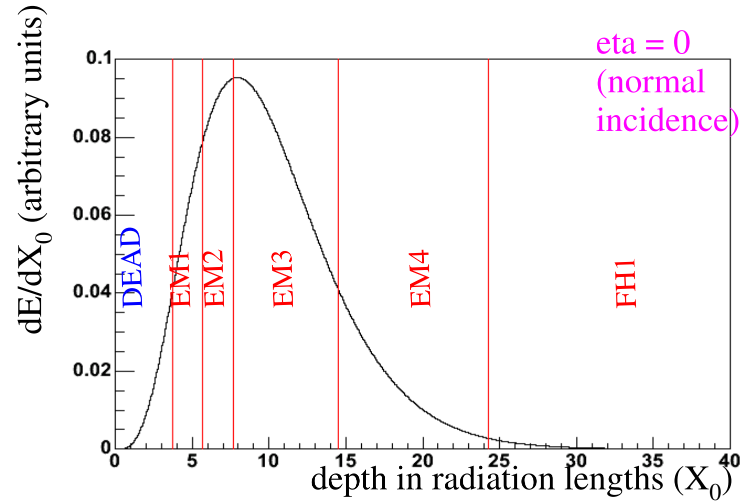
Keep in mind: the CAL is not alone !



The preshowers will finally get a new readout later this year.

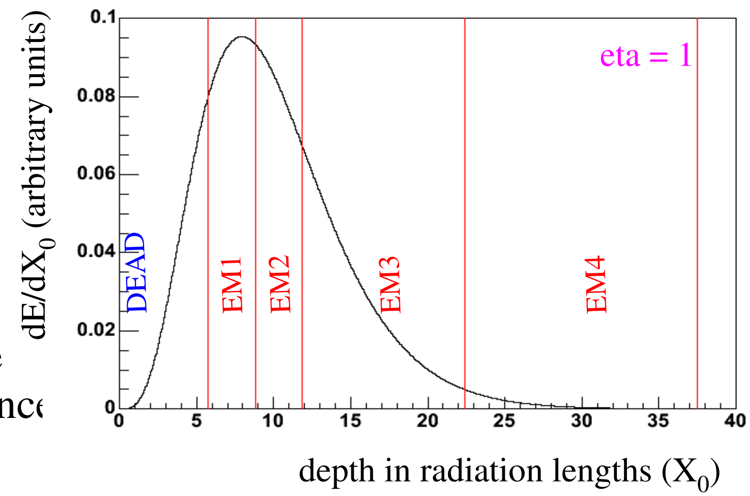
DØ Samples and weights

The plot on the right shows the average longitudinal profile of a shower with E = 45 GeV. Assuming normal incidence, the position of the active parts of the CC are also indicated.



In the reconstruction, we apply artificially high weights to the early layers (especially EM1) in an attempt to partially compensate the losses in the dead material:

Layer	depth (X_0)	weight (a.u.)	weight/X_0
EM1	2.0	31.199	15.6
EM2	2.0	9.399	4.7
EM3	6.8	25.716	3.8
EM4	9.1	28.033	3.1
FH1	≈ 40	24.885	≈ 0.6

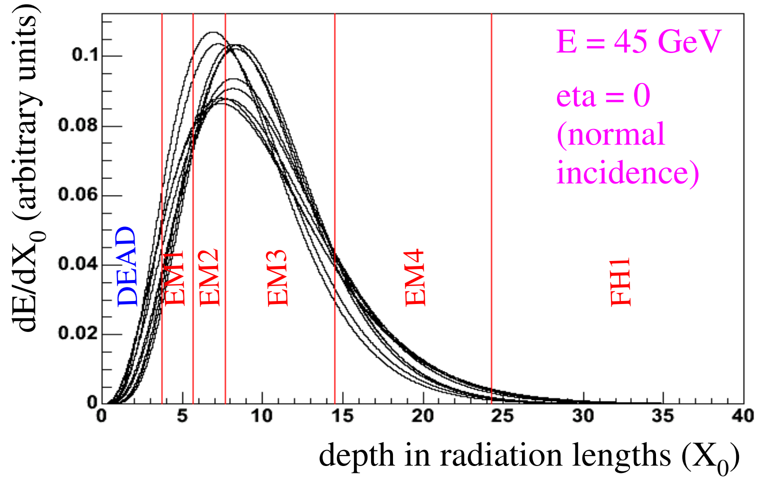


The lower plot illustrates the situation for the same average shower, but this time under a more extreme angle of incidence (physics eta = 1). The shower maximum is now in EM1 !

DØ Energy-dependence & fluctuations

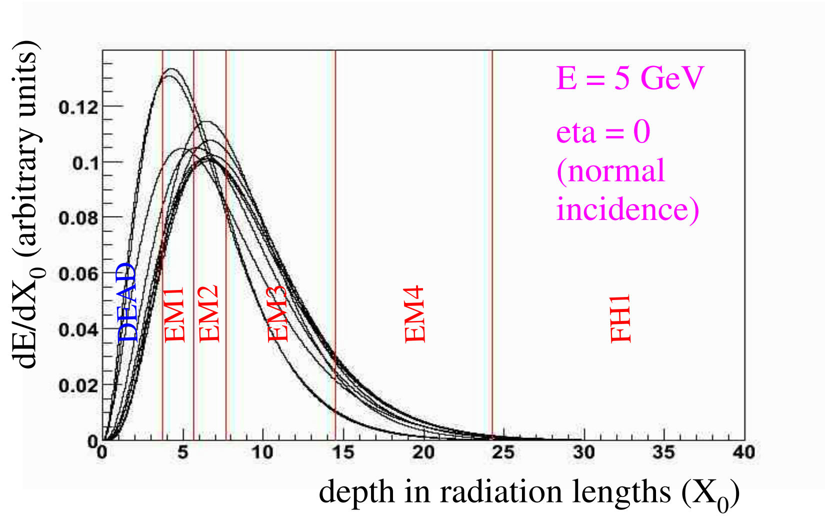
The plots on the previous slide show the *average* shower profile at E = 45 GeV.
The plot on the right is basically the same, except that it includes typical *shower fluctuations*.

=> The fraction of energy lost in the dead material varies from shower to shower.



The bottom plot illustrates the situation at a different, lower, energy. The position of the shower maximum (in terms of X_0) varies approximately like ln(E).

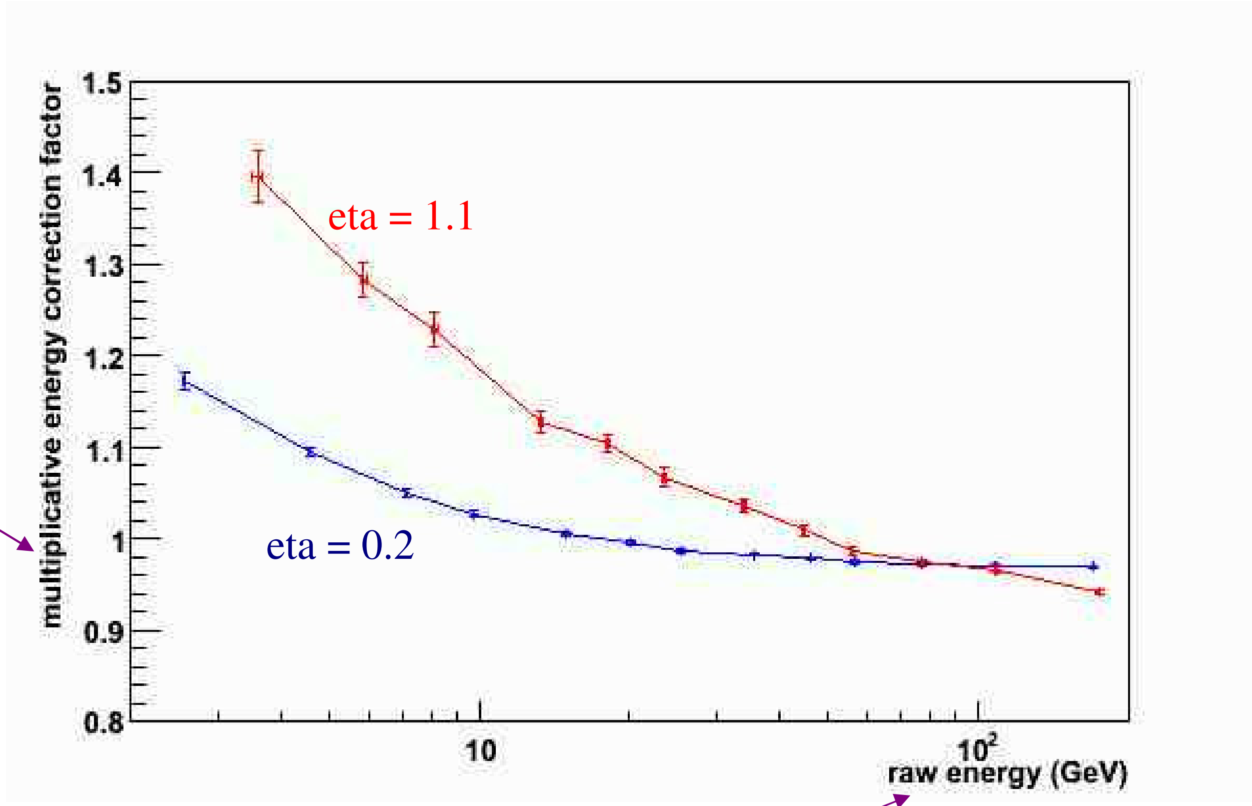
=> The average fraction of energy lost in dead material, as well as the relative importance of shower-by-shower fluctuations depend on the energy of the incident electron.



DØ average response ...

So we need to apply an energy-loss correction to our reconstructed electron energies to account for the energy lost in front of the calorimeter. This correction, as a function of energy and angle (eta) is estimated using detailed detector simulations based on Geant.

This is the energy correction factor that gets us back to the energy of the incident electron.

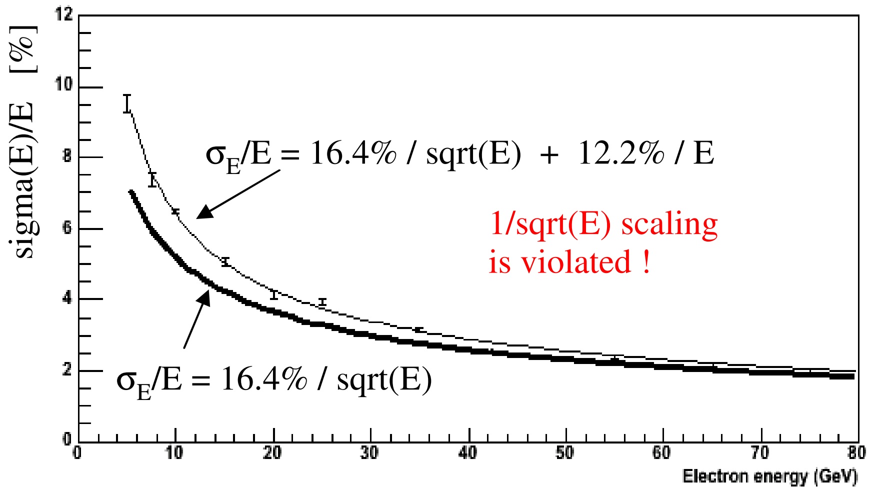


This is the energy as reconstructed in the CAL.

DØ fluctuations around the average

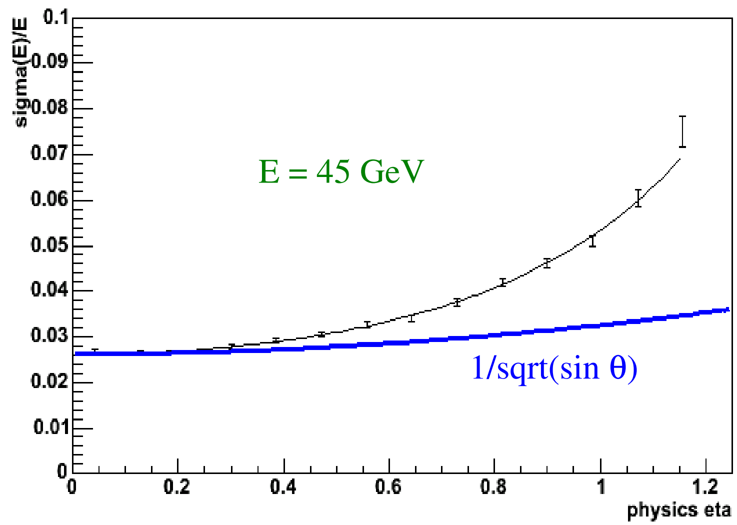
Here we show the impact on the energy resolution for electrons. This is again from a detailled detector simulation based on Geant.

Resolution at normal incidence, as a function of electron energy:



for an ideal sampling calorimeter (no dead material) one would expect this to scale as 1/sqrt(E)

Resolution at E = 45 GeV, as a function of the angle of incidence (eta):



for an ideal sampling calorimeter (no dead material) one would expect this to be almost flat

DØ EM calibration: basic idea

Factorise (roughly) into two parts:

- calibration of the calorimeter electronics,
- calibration of the device itself.

This factor can absorb any imperfection in the electronics calibration that leads to a multiplicative miscalibration that is independent of the gain path and stable in time.

Electronics calibrated using pulsers.

Calibration of the device itself:

Determine energy scale (i.e. multiplicative correction factor), ideally per cell

Use phi intercalibration to "beat down the number of degrees of freedom" as much as possible.

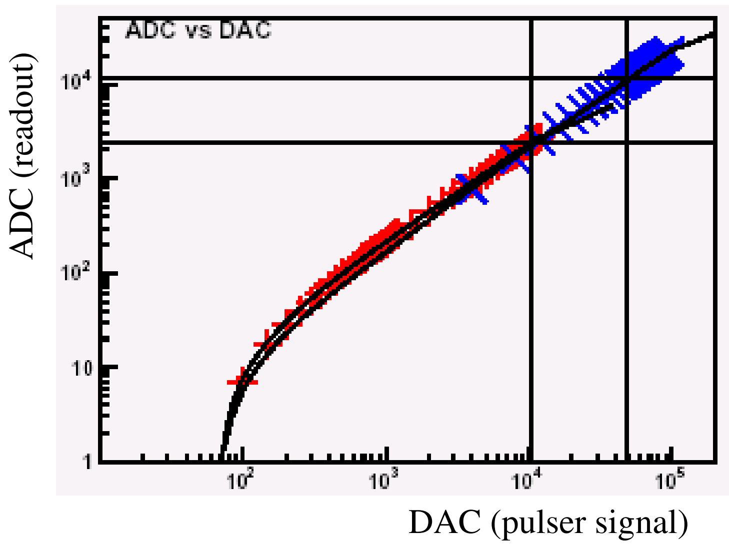
Use $Z \to e^+ e^-$ to get access to the remaining degrees of freedom, as well as the absolute scale.

Calibration of electronics: pulsers !

Aim: Pulsers are a powerful tool, both for debugging and calibration of the readout electronics.
Identify technical problems in the electronics, like e.g. dead channels.
Correct for channel-by-channel differences in electronics response.

Principle:
inject known signal into preamplifier and see what the electronics measures.

Do this separately for gains x8 and x1, optionally also separately for the two L1 SCAs per channel.



Among other things, gives handle on the non-linearities in the electronics response, which are mainly caused by the analog buffers (SCA).

Tricky part: the calibration signal is not injected at the cell level, but right before the preamps ....

Phi intercalibration

$p\bar{p}$ beams in the Tevatron are not polarised.

$\Rightarrow$ Energy flow in the direction transverse to the beams should not have any azimuthal dependence. Any ϕ dependence must be the result of instrumental effects.

Energy flow method:

Consider a given η bin of the calorimeter. Measure the density of calorimeter objects above a given E_T threshold as a function of ϕ. With a perfect detector, this density would be flat in ϕ.

Assuming that any ϕ-non-uniformities are due to energy scale variations, the uniformity of the detector can be improved by applying multiplicative calibration factors to the energies of calorimeter objects in each ϕ region in such a way that the candidate density becomes flat in ϕ ("ϕ intercalibration").

Trigger:

We collect our events using a trigger that was specially designed for this purpose.
L1: At least one EM trigger tower, low threshold.
L3: Significant EM energy in at least one of the readout towers of the trigger tower that fired L1. The threshold on the readout tower is significantly higher than the threshold on L1 trigger tower.

So far, have taken these data in dedicated special runs. Plan to collect them continuously at low rate during normal running.

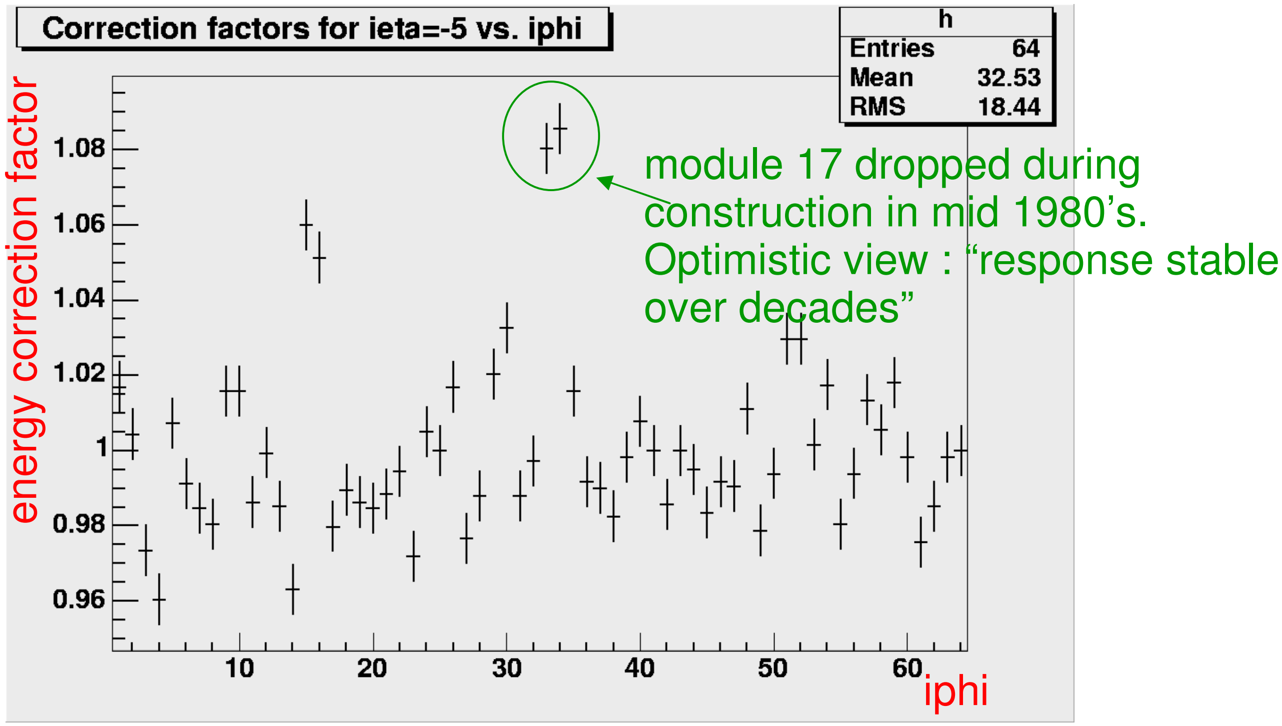
The idea is not new, see e.g. Run I: work by R. Raja, or PhD thesis by Q. Zhu (April 1994), available on the DØ web server, and refs therein. The Run II calibration has much finer granularity, though.

Phi intercalibration: results

An example of results from phi intercalibration:
determine one energy correction factor per CAL tower (EM part) at ieta = -5 .

We are exploring
a ~13 % range here

... but typically the
spread has an RMS
of the order of 3 %.

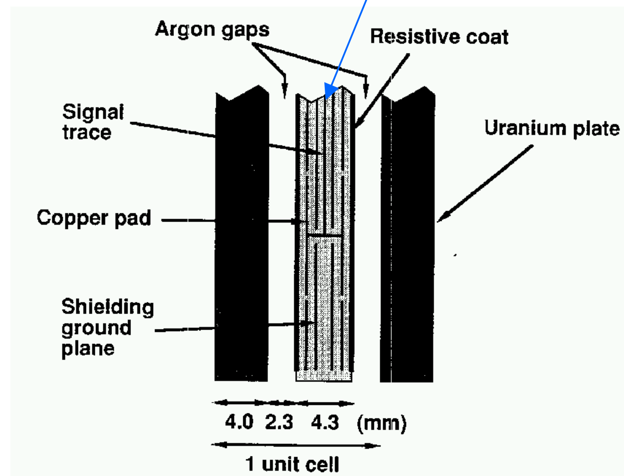


Phi intercalibration: results

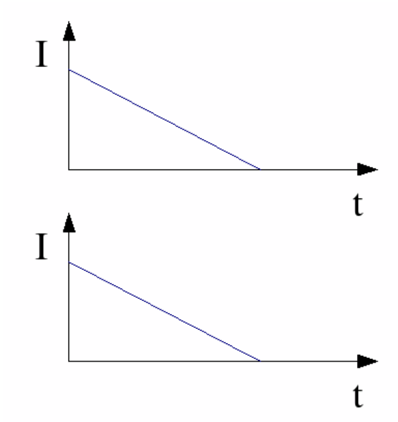
Change in electronics integration time made energy scale More sensitive to construction non-uniformities. LAR drift time 400 ns Run 1 shaping time 3 μs, Run II shaping time 400 ns. Gap non-uniformities matter now

One “*di-gap*”:

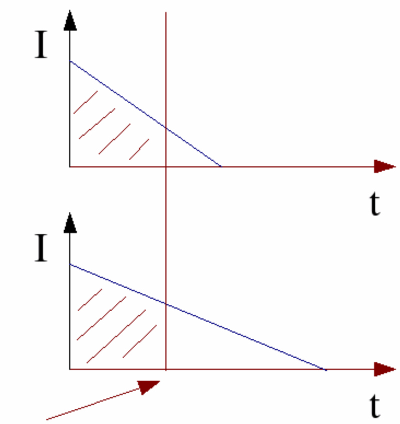
signal board



Signal from a di-gap of ideal geometry:



Response when we move the signal board away from the centre of the di-gap:



finite integration time

In the deformed case:

Infitite integration time (Run I) : We still see all the charge. Nice.
Short integration time (Run II) :
We see less charge than with perfect geometry. The fraction of the charge read out depends on the size of the displacement of the signal board.
Not good..

Fraction of charge lost due to displacement:

$dQ / Q = - (0.5 * f) / (1 - 0.5 * f) * \varepsilon^2$

f = nominal fraction of the charge that is read out
ε = fractional change of gap width due to displacement

With f = 70 %, $\varepsilon \approx 15$ % $\Rightarrow$ dQ / Q = 1 %.

For example in EM3, there are 7 di-gaps.
The effect is amplified by a factor sqrt(7) = 2.6 in the case of uncorrelated displacements.

Nick Hadley

Phi intercalibration: results

This is a photograph of an FH1 signal board. The EM signal boards are almost the same: same material, similar length, similar thickness, but roughly half the width.

Look how "wobbly" it is ! These boards are held in place between the uranium plates by a few platic spacers. "Wobbling" with a typical amplitude of 15 % or more of the gap width is not untypical.

The ruler in the photograph is 12 inches long.

Eta equalisation and absolute scale

Write reconstructed Z mass as: $m = \sqrt{2 \cdot E_1 \cdot E_2 \cdot (1 - \cos\theta)}\ ,$

E_1 and E_2 are the electron energies and θ is the opening angle from tracking.

The electron energies are evaluated as: $E_i = E_i^{\mathrm{raw}} + K\,(E_i^{\mathrm{raw}}, \vec{\alpha})\ \cdot$

raw energy measurement from the calorimeter

parameterised energy-loss correction from detailed detector simulation

With the raw cluster energy: $E_i^{\mathrm{raw}} = \sum_{j=(\mathrm{all\ cells})} c_{\mathrm{ieta}(j)} \cdot E'_j\ .$

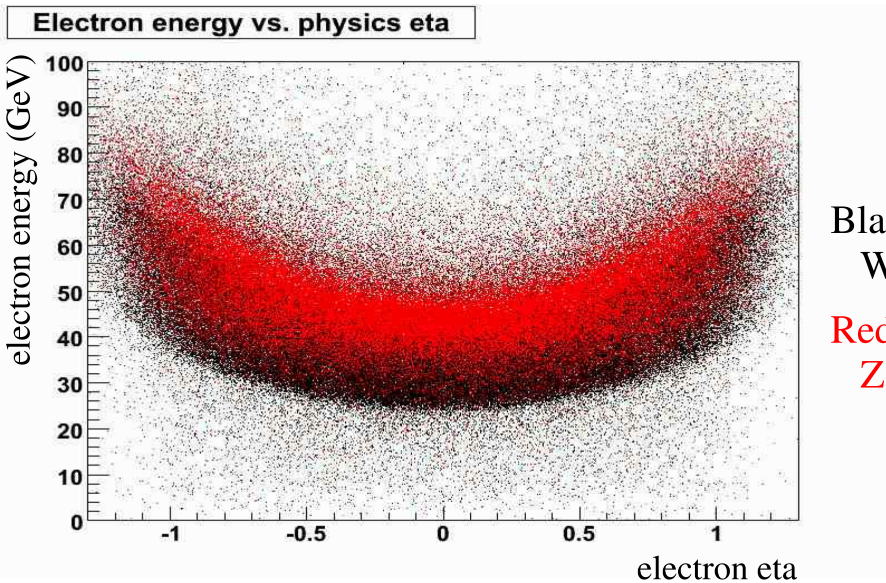
one (unknown) calibration constant per ring in eta

cell energy after electronics calibration, phi intercalibration and layer weights

Then determine the set of calibration constants c_{ieta} that minimise the experimental resolution on the Z mass and that give the correct (LEP) measured value for the Z mass.

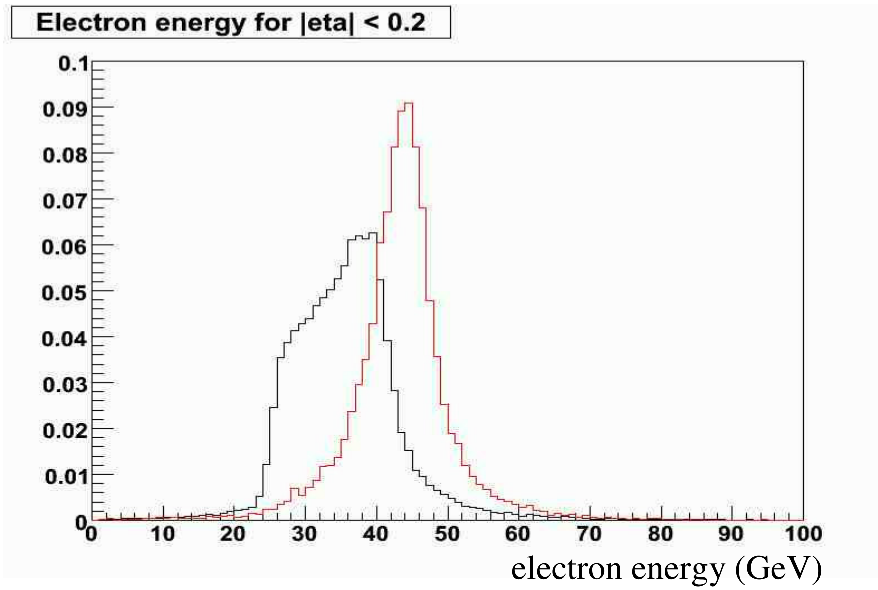
Z -> e^+e^- vs. W -> eν

If you need to be concerned at the detail level, using MC to extrapolate from known processes to the one you want to measure (in this case W->eν) may not be as straightforward as you expect.



Black:
W->eν

Red:
Z-> ee



At a given physics eta, the spread in energy of electrons from the Z is small. Also, the overlap with the energy spectrum of electrons from the W is small.

How can we test the quality of our MC predictions for the scaling of the average response and resolution from the Z down to the W ? Without any further study and just trying some "reasonable" variations of the Monte Carlo, the systematic uncertainty on the W mass would be at least 90 MeV.

Detector and Physics Calibrations
Day 2

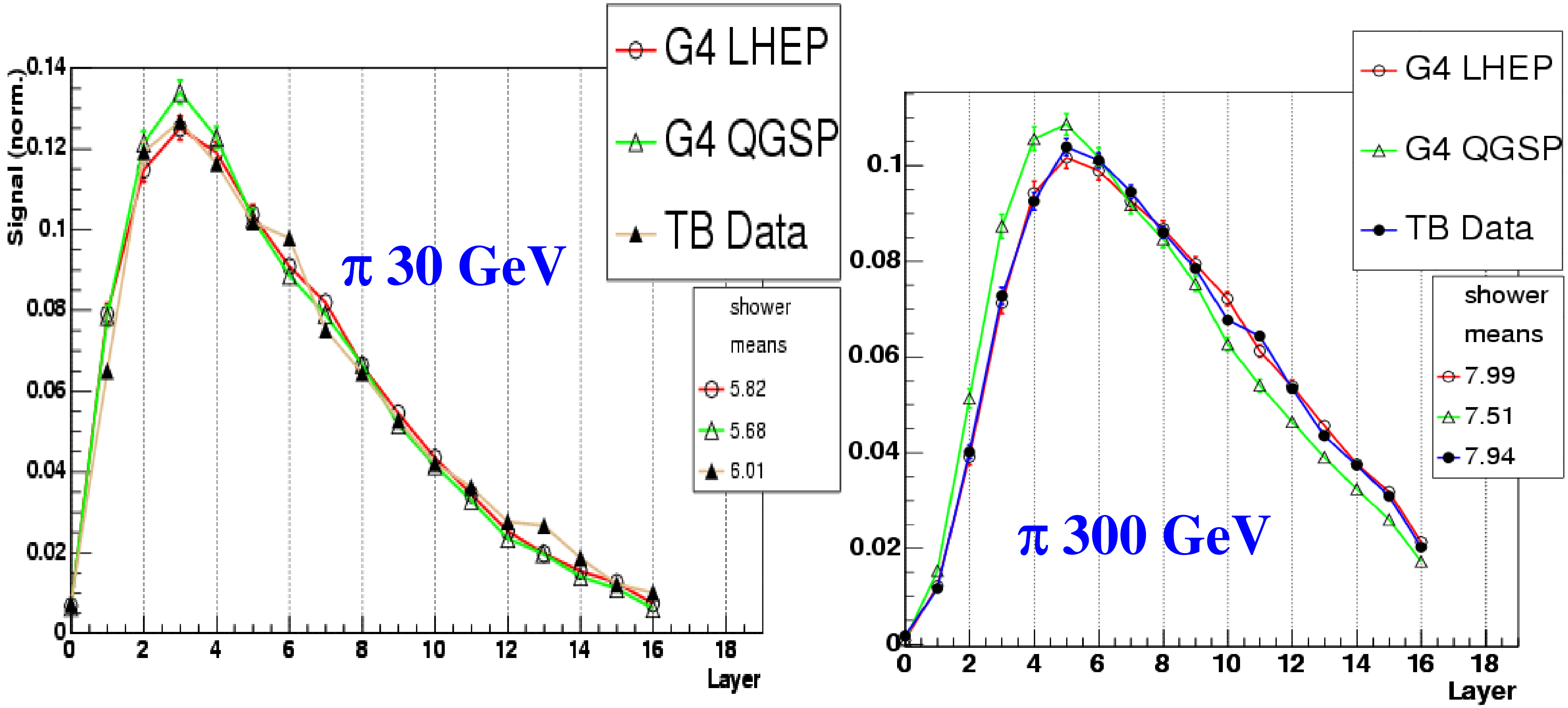
Nick Hadley
The University of Maryland

Hadron Collider Physics Summer School
Fermilab August 11-12, 2006

(CMS) HCAL Calibration

- **Use charge injection to calibrate ADCs**
- **Use sources to calibrate each tile in every *layer* of the calorimeter**
- **Use testbeam for electrons, pions and muons results to tie all the numbers together**
- **Signal seen depends on magnetic field.**
- **Must understand shower shape, radiation damage.**
- **Have lasers and LEDs for fast monitoring.**

CMS Longitudinal Shower Profile for π in HB

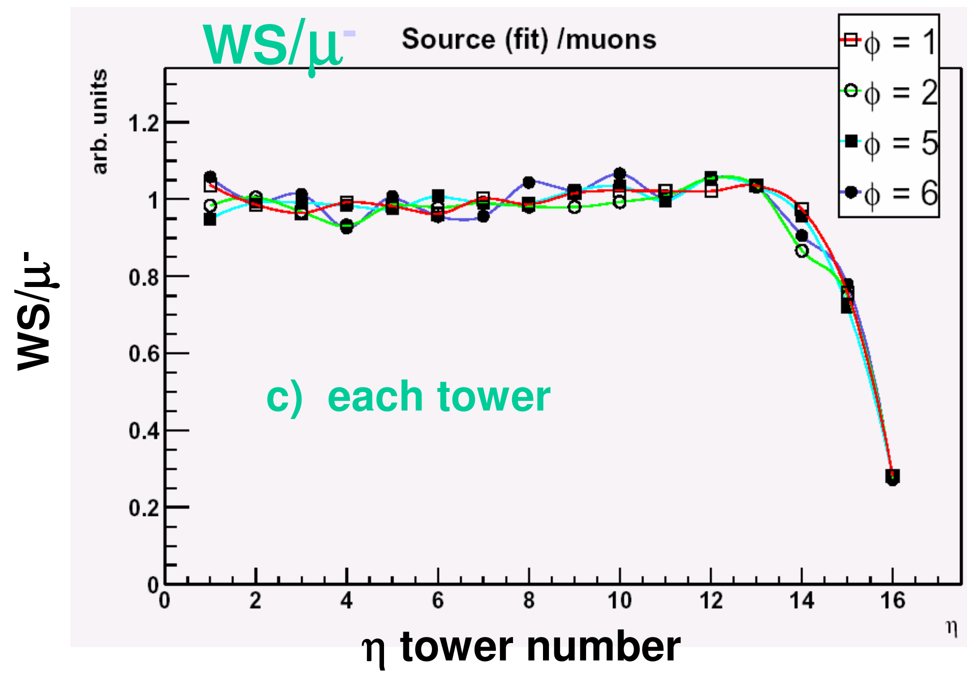


<u>**Initial Calibration Given for the Expected Mean Energy:**</u>

- **50 GeV π's for $\theta < 30^{o}$**
- **100 GeV π's for $\theta > 30^{o}$**

➔ This is why muons are not useful for HB/HE Energy Scale… they see all planes

CMS "Energy" Calibration for the source is found from the testbeam by comparing source response to 100 GeV e-

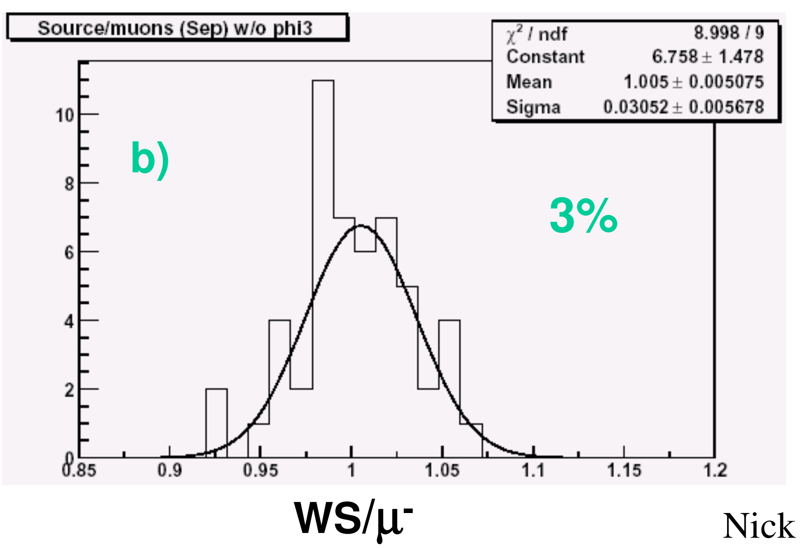


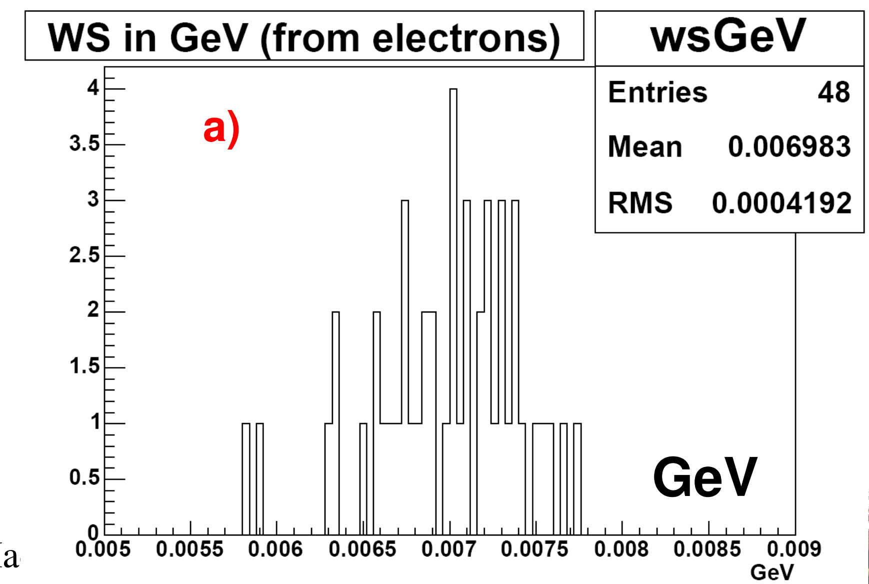
a) Calibration of source with 100GeV electron beam.

→ 6.98 MeV equivalent

date == 2005-01-31

b,c) Comparison with muon beam





HCAL Calibration

- **Important to understand your HCAL in detail. e/π response, fluctuations, electronics, aging, etc…**

- **The important topic of jet energy calibration will be covered by Beate Heinemann in her talk Monday.**

Alignment Strategy

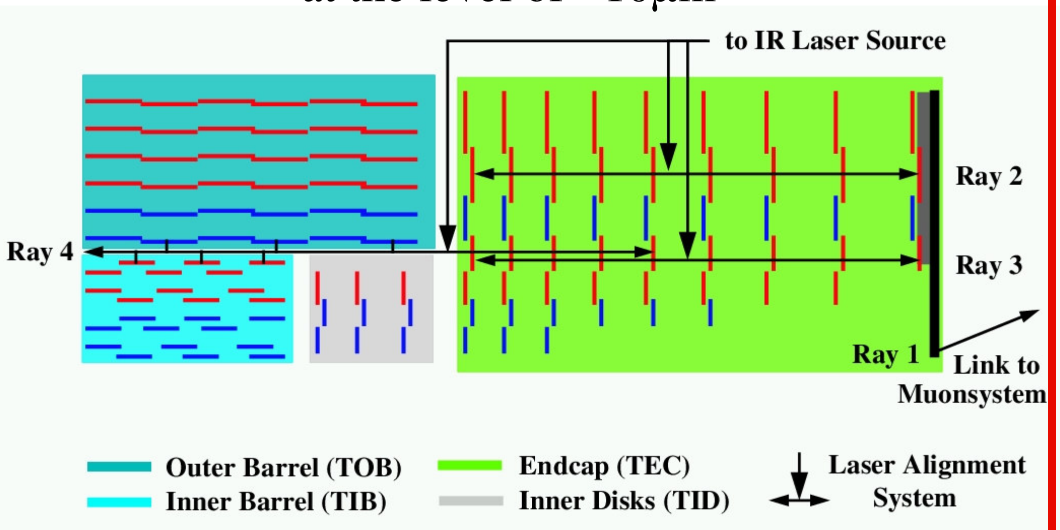
- **Applies to tracking detectors including muon chambers.**
  - Then use tracks to align calorimeters as trackers measure position better (usually) than calorimeters

- **Typically 3 step process**
  1. Measure element (e.g. wire, pixel) position during construction of subdetector using coordinate measuring machines and similar devices.
  2. Measure relative position of subdetectors after assembly using surveying techniques such as lasers.
     - Only works for detectors you can see.
  3. Track based alignment

Tracker Alignment Concept in a Nutshell

Challenge: Alignment uncertainties must not degrade intrinsic tracker resolution: ≈20µm

LAS: Aligns global support structures and will monitor relative movements at the level of ≈10µm



Mechanical Constraints:
Sensors on Modules: ≈10µm
Composted Structures: 0.1-0.5 mm

First Data Taking:

Laser Alignment
$\otimes$
Mechanical Constraints
⇒≈100µm alignment uncertainties

Sufficient for a first efficient pattern recognition.

Final Alignment: Use Tracks in order to achieve the desired level of alignment uncertainties of ≈10µm. A combination of track based alignment and laser alignment will insure an accurate monitoring of time dependent alignment effects.

Alignment Concept & Typical Numbers

	Muon	Tracker	
		Strip	Pixel
Assembly:	O(mm)	0.1-0.5mm	50-100 µm
+ Hardware Alignment:	~<100µm	<100µm	50-100 µm (no HA foreseen)
+ Track Based Alignment	~100µm (perhaps below)	~10µm	~5 µm
Remarks:	Hardware Alignment will provide the operational alignment level. Track based alignment will be a cross check and eventually a completion	Hardware Alignment will insure pattern recognition. Track Based Alignment must provide the final alignment	Only Track based Alignment. Nothing else!

Alignment Concept & Typical Numbers

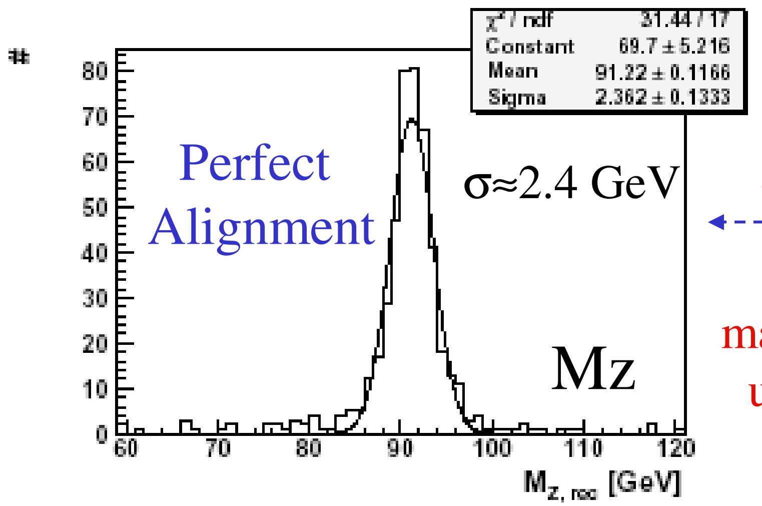
Importance of Hardware Alignment

Importance of T… Based Alignment

	Muon	Tracker: Strip	Tracker: Pixel
Assembly:	O(mm)	0.1-0.5mm	…0 µm
+ Hardware Alignment:	~<100µm	<100µm	50-100 µm (no HA foreseen)
+ Track Based Alignment	~100µm (perhaps below)	~10µm	~5 µm
Remarks:	Hardware Alignment will provide the operational alignment level. Track based alignment will be a cross check and eventually a completion	Hardware Alignment will insure pattern recognition. Track Based Alignment must provide the final alignment	Only Track based Alignment. Nothing else!

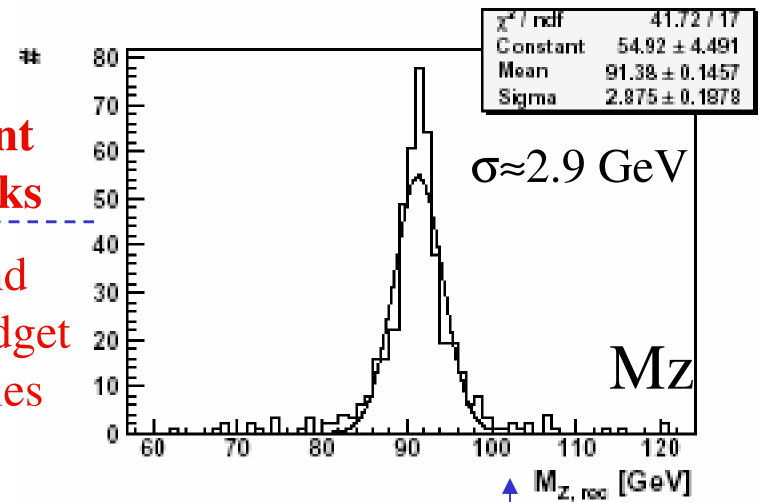
Mis-Alignment: Impact on Physics (important for Z′, LED)

⇒ Use $Z \to \mu\mu$ to illustrate the impact of mis-alignment on physics



Alignment with tracks

B field and material budget uncertainties



First Data Taking

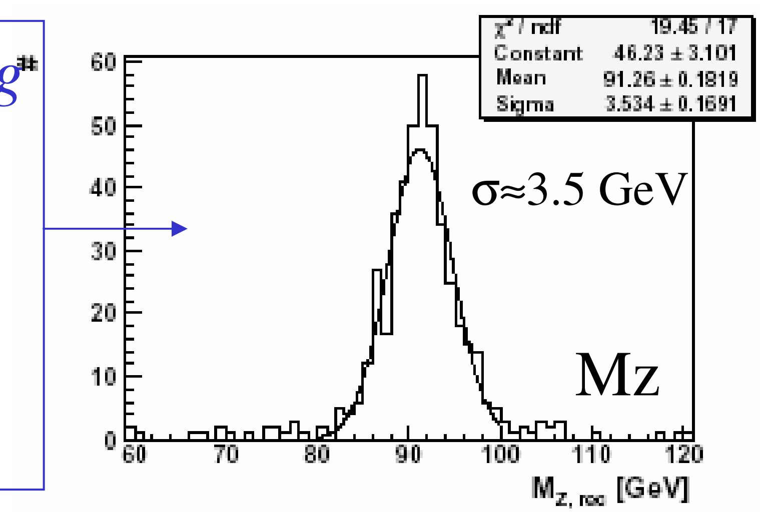
<1fb^{-1}

Laser Alignment

$\otimes$

Mechanical Constraints

⇒≈100μm alignment uncertainties



Long(er) Term:

≈>1fb^{-1}

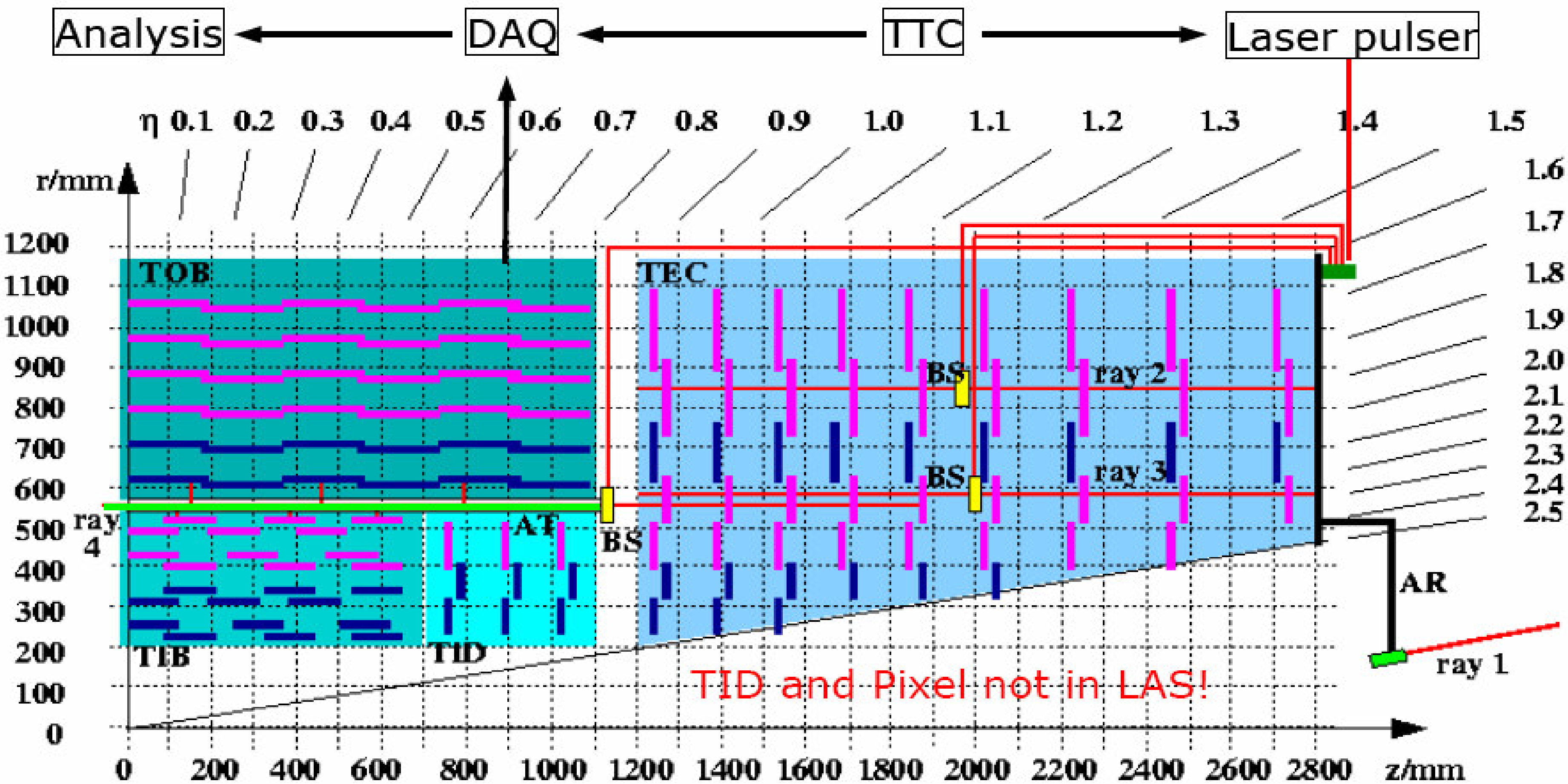
First results of Alignment with tracks

⇒≈20μm alignment uncertainties

CMS Laser System goals and concepts

- External alignment (for joint Tracker+Muon system track fit)
  - <= 150 μm measurement of Muon System position w.r.t. Tracker
  - <= 30 μrad measurement of Muon System orientation w.r.t. Tracker
- Internal alignment:
  - <= 100 μm measurement of sub-detector relative positions for track pattern recognition (between TIB and TEC, between TOB and TEC)
  - <= 50 μm for 50% of TEC petals → 70 μm for 50% of TEC modules
  - <= 10 μm monitoring of relative sub-detector position stability for track parameter reconstruction
- Main concepts Use Tracker silicon sensors and Tracker DAQ
  - No external reference structures
  - No precise positioning of LAS beams (redundancy to constrain)
  - Minimum impact on Tracker layout and production

System Overview: r-z



BS: Beam Splitter AT: Alignment tube AR: Alignment ring

"Hardware Alignment System"

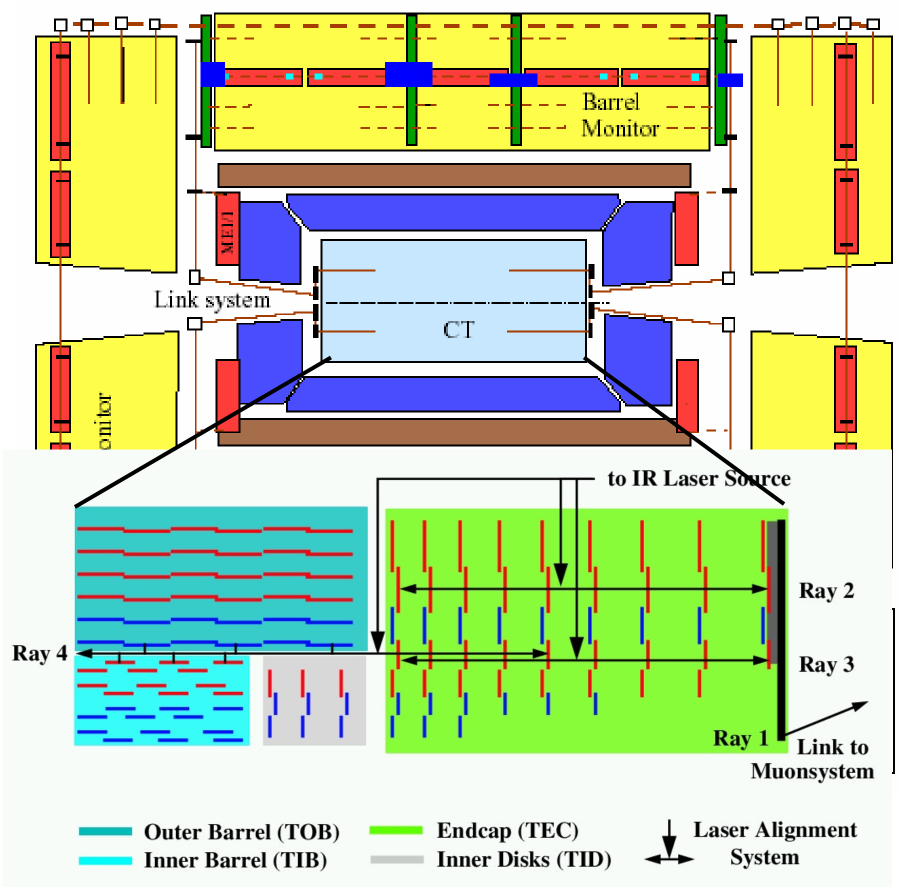
Four important ingredients:

- Internal Muon Alignment Barrel
- Internal Muon Alignment Endcap
- Internal Tracker Alignment
- Alignment of Muon w.r.t Tracker (Link System)

Specifications:

- Monitor tracker support structures at ~10µm
- Monitor Muon support structures at ~100µm
- Monitor Muon w.r.t Tracker at ~100µm

Hardware Alignment System monitors only global structures of the CMS tracking devices. The final alignment of the individual measurement units (e.g. silicon sensors) will be carried out with tracks!



Note: Only Strip Tracker and Muon System are included in the Hardware Alignment System. The PIXEL detector will be aligned and monitored with tracks only.

Nick Hadley

Track Based Alignment

- **Basic Alignment problem**
  - For each detector determine 6 parameters
    x_0, y_0, z_0 global position of center and
    φ, θ, ψ global rotation angles

- **In simplest form, a chisquared minimization problem.**
  - Can linearize if nearly aligned. Linear least squares problem. All you have to do is invert a matrix.

Want corrections $\Delta\boldsymbol{p}$ to alignment parameters, $\boldsymbol{p}$

Track parameters, $\boldsymbol{q}$

Δ_i = fitted value – measured value

$$\chi^2(\Delta\vec{p},\vec{q}) = \sum_{data\ sets}\left(\sum_{events}\left(\sum_{tracks}\left(\sum_{hits}\Delta_i^2/\sigma_i^2\right)\right)\right)$$

Nick Hadley

Aside: Linear least squares

$$\text{Fitted value} = \mathrm{y_f}(\alpha_i, \vec{x}) = \sum_{a=0}^{M} \alpha_a f_a(\vec{x})$$

$$\text{measured value} = \mathrm{y_m} \qquad w = 1/\sigma^2$$

α_a = parameters to be determined

$f_a(\vec{x})$ = known functions of $\vec{x}$ used to determine $\mathrm{y_f}$

(example straight line α_0 = intercept, $\mathrm{f}_0 = 1$, α_1 = slope, $\mathrm{f}_1 = x$)

many measurements b

$$\chi^2 = \sum_b \left(\mathrm{y_{mb}} - \mathrm{y_{fb}}\right)^2 w_b \qquad \text{minimize to find } \alpha_a$$

$$H_{ij} = \sum_b f_i(\vec{x}) f_j(\vec{x}) w_b\ , \quad u_i = \sum_b f_i(\vec{x})\, \mathrm{y_{mb}}\, w_b$$

$$\vec{u} = H\vec{\alpha} \qquad or \quad \vec{\alpha} = H^{-1}\vec{u}$$

Track based Alignment

- **Minimize chisquared by taking derivatives.**
  - Leads to a matrix equation
- **Problem is have of order 15K silicon sensors.**
- **Inverting the matrix compute time proportional to N^3, storage proportional to N^2**
  - It's a sparse matrix, which helps some.
  - Lots of nice Computer Science/Applied Math work on such problems.
- **Must fix position/orientation of one detector**
- **Additional problem, tracks not straight, and the track parameters are unknown (standard candle problem again).**
  - Once one detector aligned, easier to align others.

DØ Tracker Alignment

Alignment problem:

-	432	SMT Barrel detectors
-	144	SMT F-Disks detectors
-	96	SMT H-Disks detectors
-	152	CFT Axial Ribbons
-	152	CFT Stereo Ribbons
	976	detectors in total

For each detector in general 6 parameters are determined

x^0, y^0, z^0	-	global position of the centre
ϕ, θ, ψ	-	global rotation angles

In total $\sim$6000 parameters to determine

DØ Tracker Alignment

- "Almost" autonomous work with few parameters and switches to adjust the performance;

<u>Few numbers on program performance</u>

- about $7 \cdot 10^5$ tracks is sufficient for reasonable precision (20000 events);

- $\sim 3 \cdot 10^{-3}$ sec/track (at 1 GHz computer);

- 70 - 100 iterations;

- 1-3 days for complete alignment

<u>expected alignment precision (MC tests)</u>

SMT Axial shift precision	-	1 μm;
SMT Radial shift precision	-	4 μm;
SMT (90°) Z shift precision	-	3 μm;
SMT (2°) Z shift precision	-	18 μm;

DØ Tracker Alignment Procedure

1. Find and fit track with given geometry;

2. Compute residuals R - difference between measurement and track interpolation to given detector;

3. Express residuals $R(\Delta)$ as function of small geometry shifts Δ and construct χ^2 functional:

$$\chi^2(\Delta) = \sum \frac{|R(\Delta)|^2}{\sigma_R^2}$$

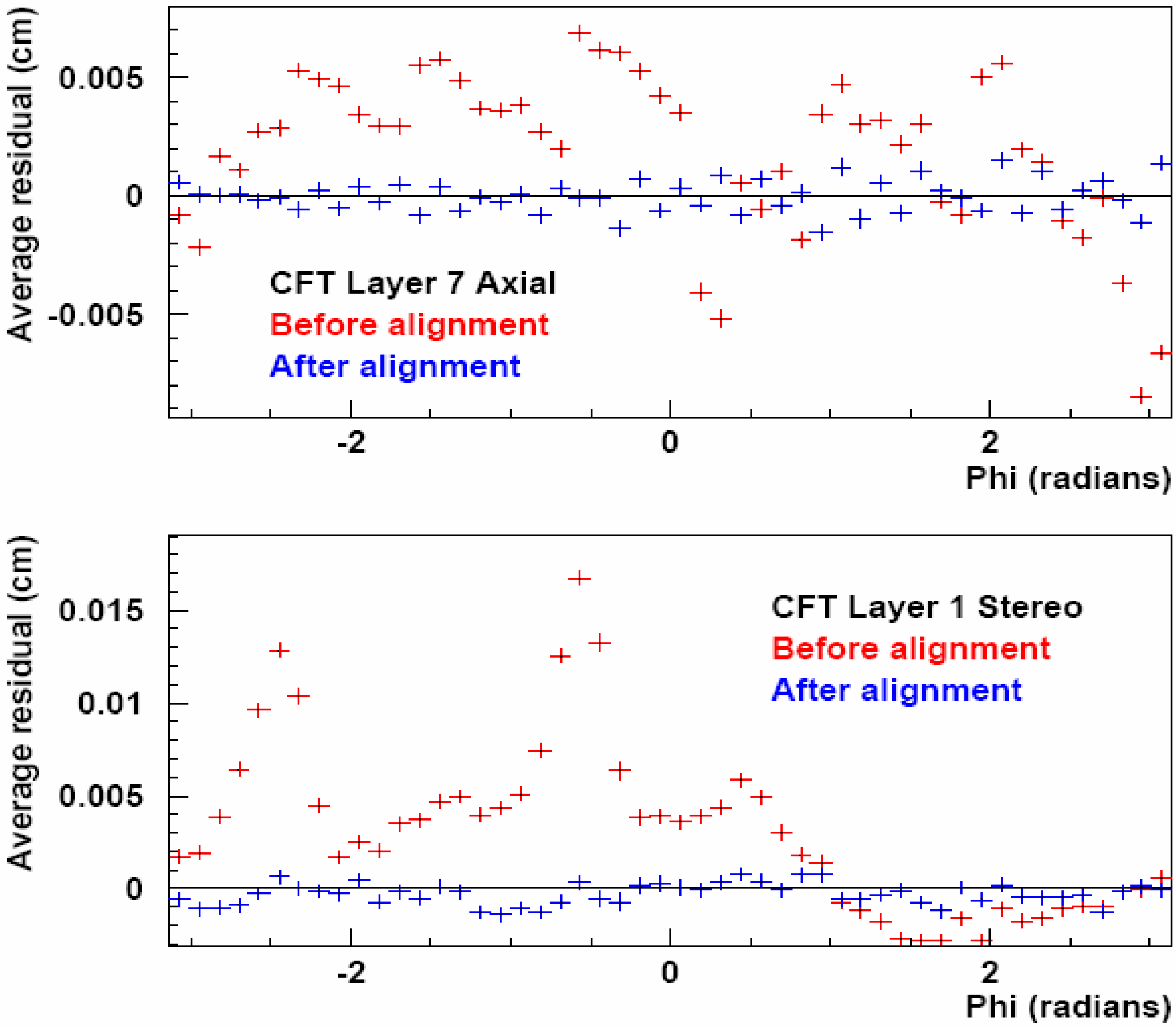
4. Find Δ from minimisation of $\chi^2(\Delta)$;

5. Apply new geometry to the track search and fit and repeat whole procedure.

Fixed detector

- We need to fix the position of some detectors;
- Special procedure, described below, allows us to fix only one ribbon for the whole D0 tracking system.
- We fix ribbon 1 in the CFT axial layer 1. This selection is arbitrary, it can be any other ribbon of CFT.

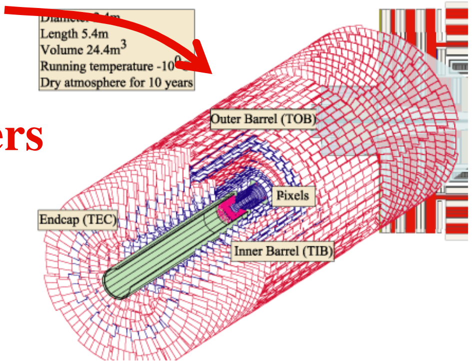
DØ Tracker Alignment Results



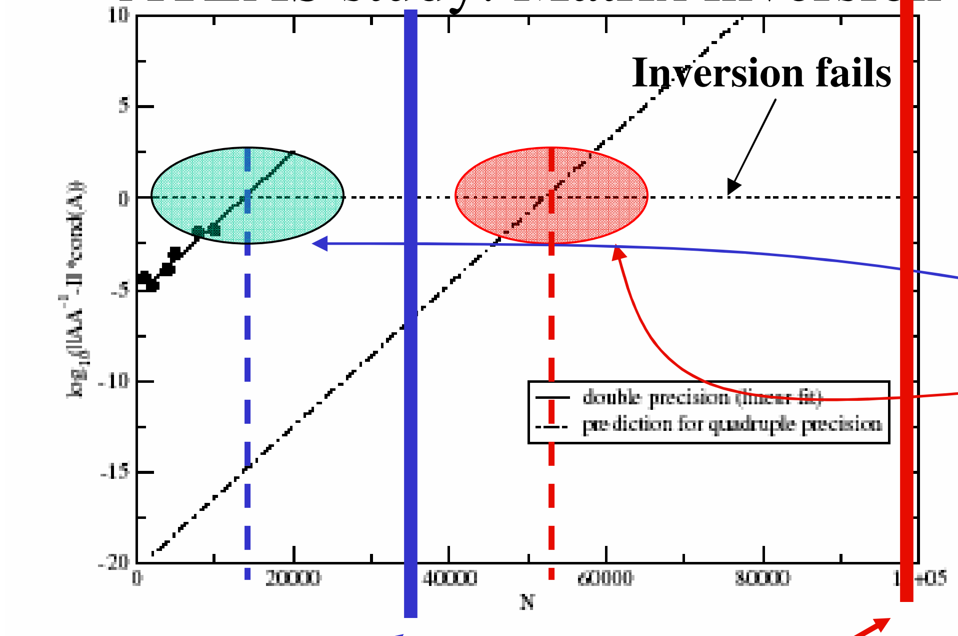
CMS Complexity of the Problem

"State of the Art Alignment" requires the inversion of large matrices!
⇒Real challenge for computing

~20000 sensors
→6x20000≈100k
alignment parameters



ATLAS study: Matrix inversion



ATLAS ID
N ~36K

CMS Tracker
N ~100K

Rounding precision:
Double vs. quadruple:
N_{max}~15000 for double
N_{max}~50000 for quadruple

Bottom Line:

The available computing resources in 2007 are probably not sufficient for a full blown "state of the art" alignment of the CMS tracker

⇒Need to pursuit new approaches!

CMS Data Samples for Alignment

The Golden Alignment Channels:

$Z \rightarrow \mu\mu$ O(20K x 2) per day

$W \rightarrow \mu\nu$ O(100K) per day

channel, NLO σ x Br	Level-1 + HLT efficiency	events for10 fb^{-1}
$W \to e\nu$, 20.3 nb	0.25	5.1×10^7
$W \to \mu\nu$, 20.3 nb	0.35	7.1×10^7
$Z \to ee$, 1.87 nb	0.53	1.0×10^7
$Z \to \mu\mu$, 1.87 nb	0.65	1.2×10^7
$t\bar{t} \to \mu + X$, 187 pb	0.62	1.2×10^6

$\Rightarrow$ Isolated well measured track statistic of one day nominal running should enable us to align all higher lever tracker structures (rod level)

A dedicated trigger stream for these event types would be very beneficial in order to insure *immediate* access to the data and, thus, a speedy alignment of the tracker!

Bottom Line:

Isolated high momentum (p_T ~50-100 GeV) muon tracks seem to be the first choice for the alignment

$\Rightarrow$ Need special stream for these events!

Exploit mass constraint:

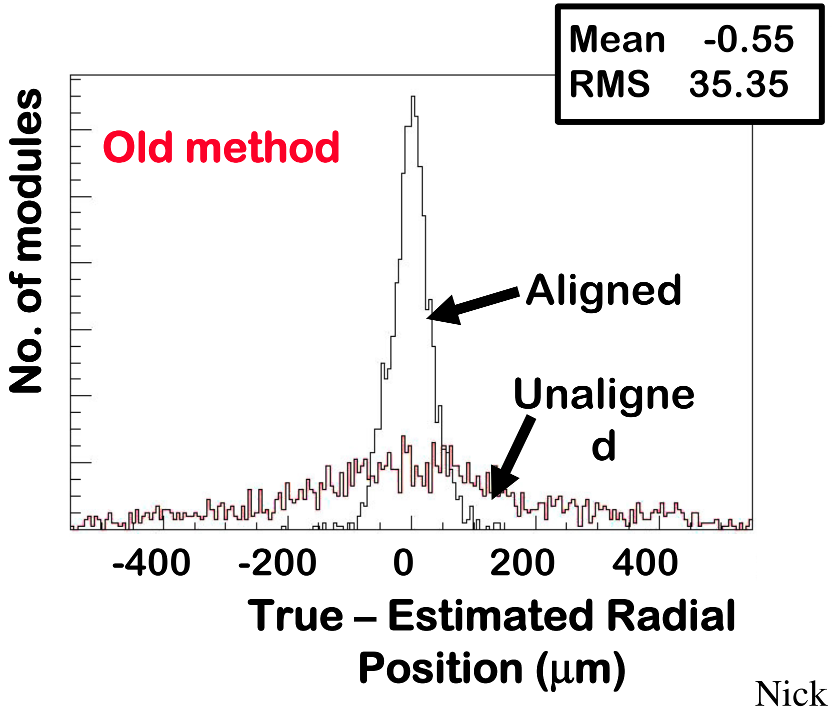
Properly including the mass constraint for $Z \rightarrow \mu\mu$ (or even $J/\phi \rightarrow \mu\mu$) will significantly enlarge our capability two align also detectors wrt each other which are not crossed by single collision tracks

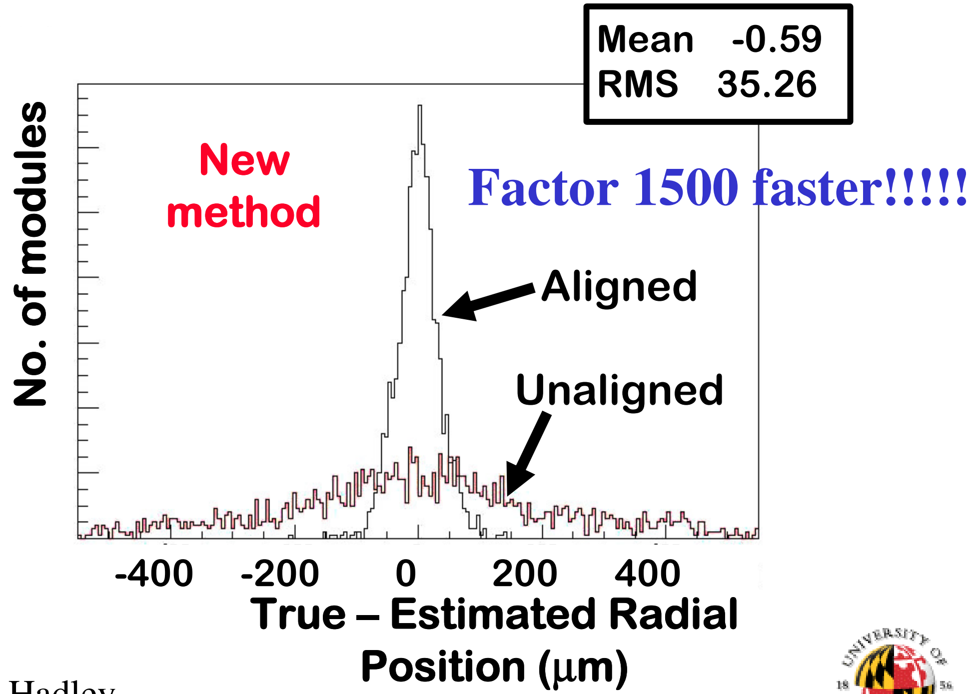
CMS implementation of Millepede II Algorithm (Millepede see www.desy.de/~blobel)

Original Millepede method solves matrix eqn. A x = B, by inverting huge matrix A.
This can only be done for < 12000 alignment parameters.

New Millepede method instead minimises |A x – B|.
Is expected to work for our 100000 alignment parameters.

Both successfully aligned ~12% of Tracker Modules using 2 million $Z \to \mu^+ \mu^-$ events.
Results identical, but new method 1500 times faster !



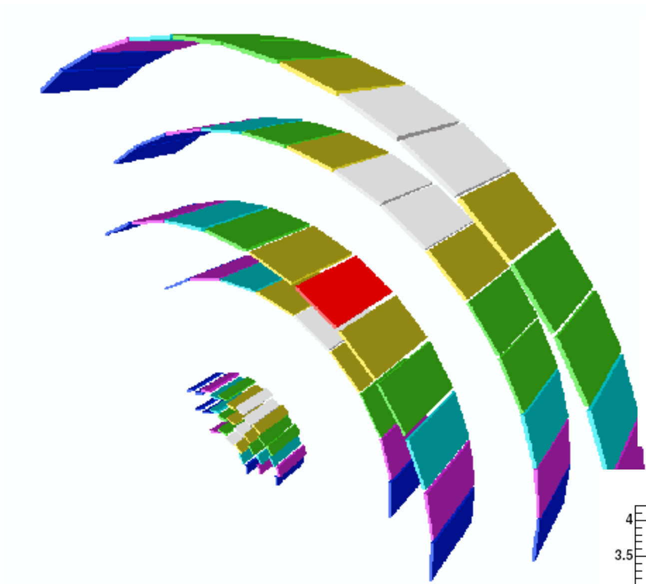


CMS Kalman Filter

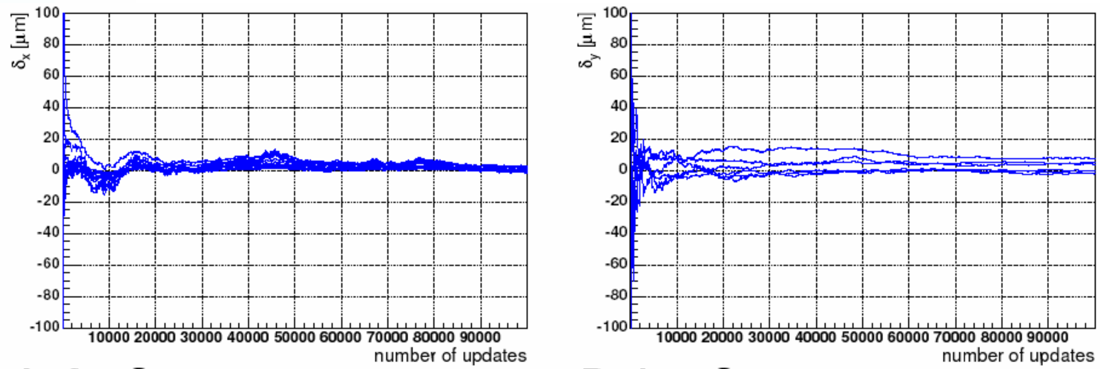
- Iterative method (track-by-track) for global alignment using charged tracks: The alignment parameters and the corresponding variance-covariance matrix are updated after each track.
- Update is not restricted to the detector units that are crossed by the track, but also detector units that have significant correlations with the ones in the current track are taken into account.
- Certain amount of bookkeeping is required ("update lists").
- No inversion of large matrices.
- Possible to use prior information about the alignment obtained from mechanical and/or laser measurements.
- For a CMS-like setup the method works, a first implementation in ORCA exists.

Kalman Filter alignment

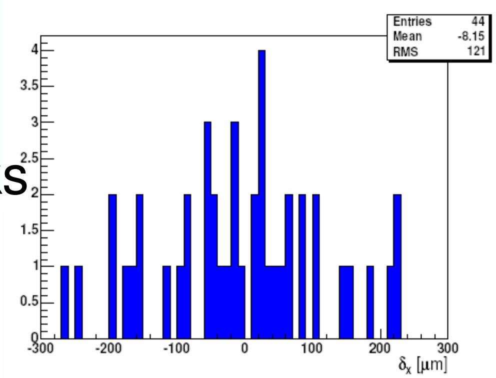
Alignment of the TIB

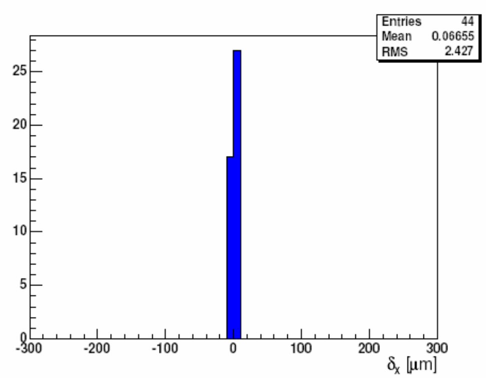


After 100K single muon tracks



Left: Convergence in x in μm, Right: Convergence in y in μm





600 μm

2 μm

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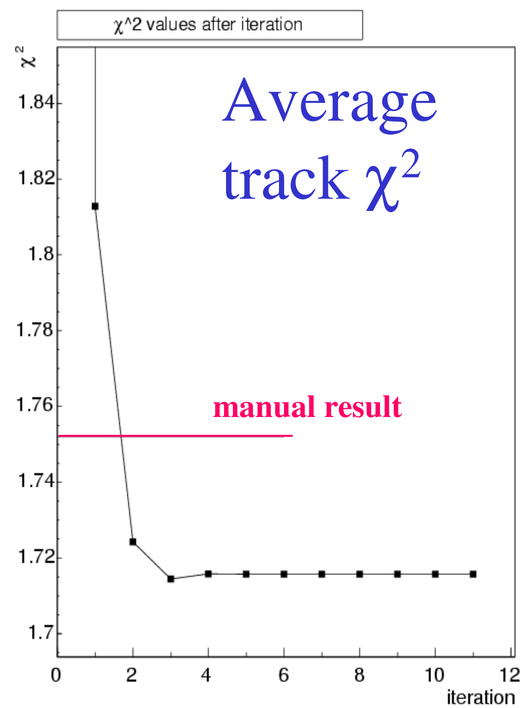
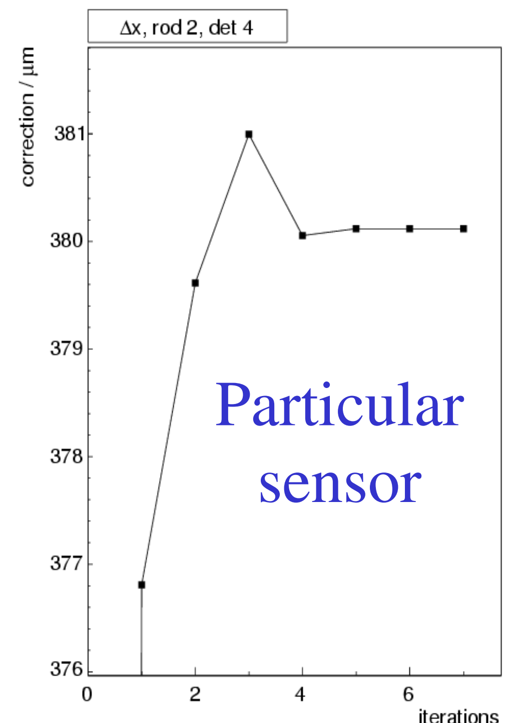
CMS Hits and Impact Points (HIP) Algorithm

- Collect a sample of tracks
- Align individual sensors independently
- Reconstruct tracks and iterate
- Low computational cost, 6 x 6 matrix per sensor
- Algorithm studied with real data: CRack test beam and cosmic data (8 genuine alignable strip detectors)
- Proof of principle for alignment software implementation in CMS software
- Larger cosmic data sample expected

- Tests using testbeam and cosmic data ongoing





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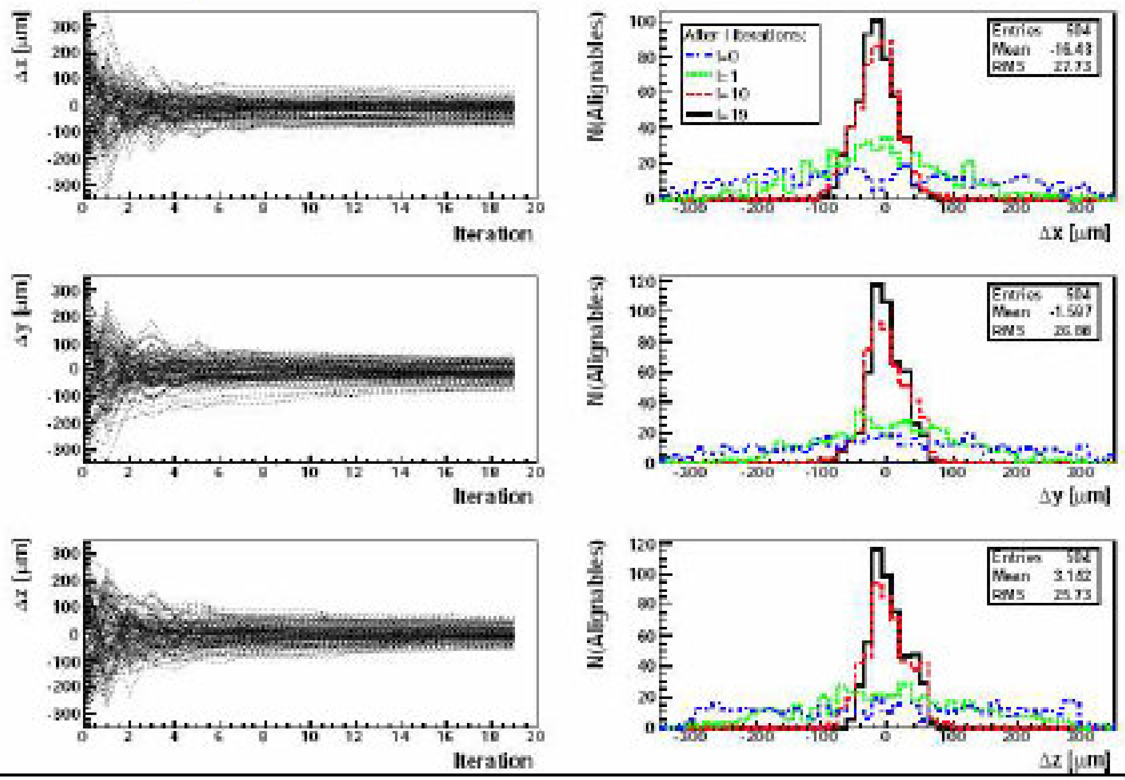
Results from pion test beam data

CMS HIP Algorithm

- Stand-alone alignment of Pixel Barrel modules
- Track curvature obtained from track-fit of full Tracker (even mis-aligned Tracker)

Convergence of estimates | Distribution of local shifts



CMS PTDR-Section 6.6 – Alignment (https://cmsdoc.cern.ch/cms/cpt/tdr/)

- **Initial surveys and starting alignment**
  - Module mounting precision known from the surveys to about 100 μm
  - Laser Beams will be able to monitor the *global tracker elements* wrt other subsystems (e.g. Muons) to about 100 μm
- **Data taking alignment will be done using tracks**
  - Two scenarios foreseen
    - 1 fb^{-1}
      - Pixels will have ~10 micron residuals
      - Silicon strip detector ~ 100 micron
    - 10 fb^{-1}
      - All systems aligned to ~10 micron
- **Three methods currently exploited**
  - HIP
    - χ^2 based large 6Nx6N matrix inversion, block diagonalized
    - Especially suited for pixel alignment
  - Millipede
    - Based on the inversion of large matrices, including track parameters
      - CDF and H1 already used
    - New fast version implemented successfully for CMS
  - Kalman filter
    - Iterative method track-by-track
    - Update alignment parameters after each track

CMS Track Based Alignment References

- **In flux, Google search to get many talks and papers**
- **Good list of alignment references**
  http://www4.rcf.bnl.gov/~fisyak/star/References.html
- **HIP Algorithm** **(CMS-CR-2003/022)**
  - V. Karimaki, T. Lampen (Helsinki), F.-P.S. (CERN)
  - Robust and straightforward, but no correlations between sensors
- **Kalman Filter**
  - R. Fruehwirth, W. Adam, E. Widl (Vienna); also M. Weber(Aachen)
  - Novel approach, full treatment of correlations, w/o large matrix inv.
- **V. Blobel's Millepede** **(new version of Millepede II will avoid matrix inversion)**
  - M. Stoye/PhD, G. Steinbrueck (Hamburg)
- **Simulated annealing**
  - A. le Carpentier/PhD, E. Chabanat (Lyon)

General References

ATLAS Physics TDR

http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html

CMS Physics TDR

http://cmsdoc.cern.ch/cms/cpt/tdr/